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RĪGA STRADIŅŠ UNIVERSITY

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Development of the Electricity Demand Response Mechanism for Renewable Integration and Consumer Engagement in Latvia

Doctoral Thesis for obtaining a doctoral degree
"Doctor of Science (*Ph.D.*)"

Sector – Economics and Business
Sub-Sector – Regional Economics

Riga, 2022

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Riga, 2022

Abstract

The key principle of electricity market design is the maximisation of public welfare. In the context of rational electricity consumption, social welfare is the sum of consumer surplus, supplier surplus and congestion rents in order to maximise the benefits to society. For decades, the importance of balancing supply and demand has been emphasised in discussions on the security of the electricity sector. It has been reasonably assumed that electricity demand is inelastic, mainly by studying supply potential. However, the current understanding of supply and demand in the electricity system needs to address the three main challenges of European energy policy: sustainability, security of supply and competitiveness, while guaranteeing fairness in energy distribution.

The aim of the research is to develop a conceptual framework for the integration of renewable energy sources and consumer involvement, based on the technology of a Demand Response aggregator – an information and technology company – in the Latvian electricity sector.

The Thesis consists of an introduction, four chapters, conclusions, recommendations and a bibliography. The introduction explains the actuality of the research topic, defines the aims and objectives of the research, its subject and object, puts forward the research hypothesis, and determines the scientific novelty and practical significance of the research. In the first and second chapters, a theoretical and methodological framework, economic and institutional foundations and peculiarities of Demand Response in the energy sector, electricity price factors, the new role of electricity end-users and the possibilities of optimising demand response are provided. In the third chapter, the author analyses the macroeconomic and physical indicator trends of the energy sector, the renewable energy sources and electricity system prices, calculates approximate dependence formulae and coefficients of determination; develops a methodology for a comprehensive analysis of correlation and regression dependence of physical and system price indicators of the electricity sector based on an appropriate adaptation of classical mathematical models, and contributes to the literature on the impact of the state aid on the electricity market. In the fourth chapter, the author has proposed and developed a new two-level technical model for optimisation of demand response services, which proposes to solve the problem of reducing electricity consumption in the first stage and, in the second stage, to solve the optimisation problem of which group of active consumers' loads to disconnect in case of electricity shortages, thus, to respond to electricity market prices.

The main text of the Thesis is 155 pages. The bibliography contains 137 sources. Additionally, 48 tables, 31 figures and 2 annexes are included in the Thesis.

Keywords: demand side management, electricity Demand Response, active end-users, renewable energy, regional aggregator, demand response service model.

Anotācija

Elektroenerģijas pieprasījuma reakcijas mehānisma attīstības veicināšana ar atjaunīgo energoresursu integrāciju un patērētāju iesaisti Latvijā

Elektroenerģijas tirgus noskaidrošanas galvenais princips ir sabiedrības labklājības maksimizācija. Elektroenerģijas racionāla patēriņa kontekstā, lai sabiedrība iegūtu maksimālu labumu, sociālā labklājība ir patērētāju pārpalikuma, piegādātāju pārpalikuma un pārslodzes rentes summa. Jau gadu desmitiem, diskutējot par elektroenerģijas nozares drošību, tiek uzsvērta piedāvājuma un pieprasījuma līdzsvara nozīme. Vienlaikus, pētot galvenokārt piedāvājuma potenciālu, pamatoti ir pieņemts, ka pieprasījums pēc elektroenerģijas ir neelastīgs. Tomēr, lai risinātu trīs galvenos Eiropas enerģētikas politikas uzdevumus – ilgtspējību, piegādes drošību un konkurētspēju, vienlaikus garantējot enerģijas sadales taisnīgumu, – pašreizējā izpratne par elektroenerģijas sistēmas piedāvājumu un pieprasījumu ir jāaktualizē.

Pētījuma mērķis ir izstrādāt elektroenerģijas pieprasījuma reakcijas konceptuālo ietvaru atjaunīgo energoresursu integrācijai un patērētāju iesaistei, balstoties uz pieprasījuma reakcijas agregatora – informācijas un tehnoloģiju uzņēmuma – tehnoloģiju, Latvijas elektroenerģijas sektorā.

Promocijas darbs sastāv no ievada, trim nodaļām, secinājumiem, priekšlikumiem un literatūras saraksta. Ievadā tiek pamatota pētījuma tēmas aktualitāte, definēti tā mērķi un uzdevumi, priekšmets un objekts, izvirzīta pētījuma hipotēze, kā arī noteikta pētījuma zinātniskā novitāte un praktiskais nozīmīgums. Pirmajā un otrajā nodaļā sniegts teorētiskais un metodoloģiskais ietvars, pieprasījuma reakcijas ekonomiskie un institucionālie pamati un īpatnības enerģētikas nozarē, elektroenerģijas cenu faktori, elektroenerģijas galalietotāju jaunā loma un pieprasījuma reakcijas optimizācijas iespējas. Trešajā nodaļā autore argumentēti analizē enerģētikas nozares makroekonomisko un fizisko rādītāju, atjaunīgo energoresursu un elektroenerģijas sistēmas cenu tendences, aprēķina aptuvenās atkarību formulas un determinācijas koeficientus; ir izstrādāta metodoloģija elektroenerģijas nozares fizisko un sistēmas cenu rādītāju korelācijas un regresijas atkarību visaptverošai analīzei, pamatojoties uz atbilstošu klasisko matemātisko modeļu adaptāciju, tiek papildināta literatūra par valsts atbalsta ietekmi uz elektroenerģijas tirgu. Ceturtajā nodaļā autore izvirza, izstrādā un pamato jaunu divlīmeņu pieprasījuma reakcijas pakalpojumu optimizācijas tehnikas modeli, kura pirmajā posmā tiek piedāvāts risināt elektroenerģijas patēriņa samazināšanas problēmu un otrajā posmā – risināt optimizācijas problēmu, kādas aktīvo patērētāju grupas slodzes atslēgt, ja elektroenerģijas daudzums ir nepietiekams, un tādējādi reaģēt uz elektroenerģijas tirgus cenām. Darba nobeigumā ir formulēti secinājumi un priekšlikumi.

Darba pamatteksts izklāstīts 155 lappusēs. Bibliogrāfisko sarakstu veido 137 avoti. Promocijas darbā ir 48 tabulas, 31 attēls un 2 pielikumi.

Atslēgvārdi: pieprasījuma vadīšana, elektroenerģijas pieprasījuma reakcija, aktīvie galapatērētāji, atjaunīgie energoresursi, reģionālais agregators, pieprasījuma reakcijas pakalpojumu modelis.

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Abbreviations used in the Thesis

AC	Active consumer
CEP	Clean Energy Package
CO2	Carbon dioxide
CEEP	Clean Energy for all Europeans Package
DA	Day-ahead electricity prices
DAM	Day-ahead Market
DERs	Distributed energy sources
DM	Demand Management
DR	Demand Response
DSOs	Distribution system operators
ENTSO-E	European Network of Transmission System Operators for Electricity
IBDR	Incentive-Based Demand Response
ISO	Independent System Operator
ICTs	Information and communication technologies
IPBDR	Incentive Payment-Based Demand Response
KP	Integer optimization “Knapsack Problem”
PBDR	Price-Based Demand Response
P2P	Peer-to-Peer
TSO	Transmission System Operator
VRE	Variable Renewable energy

Introduction

When arguing for the relevance of a doctoral dissertation, it would be correct to start by thinking about the nature of substantial changes in society. Sustainable Development and Sustainable Development Goals[1] has clearly become one of these changes suggested by the United Nations. Currently the nations are dealing with an evolutionary process, the causes of which go back at least to the times of the first industrial revolution. It is believed that, because of it, the population has increased rapidly, and production has been developing. Human beings have been exploiting wealth from nature and the volume of wastes and pollutants thrown into the environment has gradually increased. Preserving the global life support systems has become more difficult due to the rapid and continuing human-caused environmental changes.[2] Furthermore, the current geopolitical tensions, based on Russian invasion in Ukraine, the European Commission proposed a document "REPowerEU: Joint European action for more affordable, secure and sustainable energy".[3] According to the President of the EC: "The quicker we switch to renewables and hydrogen, combined with more energy efficiency, the quicker we will be truly independent and master our energy system"[4]

By the EU the term Sustainable Development was mentioned in the 2001 EU Sustainable Development Strategy, in the first EU policy document detailing ways for the EU to use resources efficiently, and calling for better coordination between competing economic, environmental, and social sustainability policies.[5] However, the initial attempt to define environmental sustainability considered the First Environmental Programme in 1973. Thus, in the course of the past five decades, since the adoption of one, EU environmental policy and legislation have expanded dramatically, and gradually become one of the main EU areas of intervention.

At the same time, Stimson et al[6] offers the following definition: "Regional Economic Development is the utilization of economic processes and available resources that result in the sustainable development of the region and the desired economic development results for the

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[1] Sustainalbe Development. United Nations. https://sdgs.un.org/goals. [Accessed: 12.08.2020]

[2] Shi, L., Han, L., Yang, F., Gao, L. 2019. The Evolution of Sustainable Development Theory: Types, Goals, and Research Prospects. *Sustainability*. 11(24):7158. https://doi.org/10.3390/su11247158. [Accessed: 12.08.2020]

[3] REPowerEU: Joint European action for more affordable, secure and sustainable energy. European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_1511. [Accessed: 08.03.2022]

[4] *Ibid*.

[5] Council of the European Union. 2001. Presidency Conclusions Göteborg European Council, 15 and 16 June 2001. [Accessed: 12.08.2020]

[6] Stimson, R., Stough, R., Roberts, B. H. 2002. Regional Economic Development: Analysis, and Planning Strategy, Springer, Berlin.

region and that meet the values and expectations of entrepreneurs, residents and immigrants.” Further emphasizing that regional economic development is:

1) the use of economic processes and available resources that result in the sustainable development of the region and the results of economic development desired for the region;
2) the process in which regional (local) government or community organizations are involved in order to stimulate or maintain business activity and / or employment;
3) a combination of qualitative and quantitative aspects of the region's economy;
4) structural features, such as the capacity to maximize the remaining benefits in the region and the ability to generate new economic activity.

The **topicality and relevance** of the Thesis is due to the emergence of new components both in the relationship between society and new technologies, and the emergence of new substantial systems in the electricity sector. As a result, insufficient understanding of the complexity and multifacetedness of the problem, as well as of the multiplicity of actors involved in the situation. The main principle of electricity market clearing is maximization of the social welfare.[7] The social welfare is the sum of the consumer surplus, the supplier surplus and the congestion rent. For decades, debating the safety of the electricity sector has emphasized the importance of supply and demand balance. At the same time, studying mainly the supply potential, reasonably assumed that the demand for electricity is inelastic. However, in order to address the three major challenges of European energy policy: sustainability, security of supply and competitiveness while guaranteeing energy equity,[8] the present understanding of electricity system supply and demand need to be actualized. Following the liberalization of electricity markets, discussions have shifted the focus of security on measures from the supply side. Besides increasing generation capacity, demand should also be exploited.[9] Emerging deployment of information and communication technologies (ICTs), power electronics, for example, smart meters, and distributed energy resources[10] endanger the security of electricity sector, thus the need for transition. In addition, an activation of the role of the consumer in the transition should be addressed.

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[7] NEMO Committee. 2019. EUPHEMIA Public Description. Single Price Coupling Algorithm, [Online]. Available: http://www.nemocommittee. [Accessed: 12.09.2020] eu/assets/files/190410_Euphemia %20Public%20Description%20version%2

[8] Mengolini, A. M. 2017. Prosumer behaviour in emerging electricity systems. PhD thesis, DOI:10.6092/polito/porto/2675327 [Accessed: 12.09.2020]

[9] Koliou, E., Eid, Ch., Chaves-Ávila, J. P., Hakvoort, R. A. 2014. Demand response in liberalized electricity markets: Analysis of aggregated load participation in the German balancing mechanism, Energy, Volume 71, 245–254, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2014.04.067. [Accessed: 12.09.2020]

[10] Distributed energy sources (DERs) - e.g., gasfired distributed generation, solar PV, small wind farms, electric vehicles, energy storage, and demand response.

In open electricity markets, the use of demand response comes with a risk of conflict of interest between different parties. Nevertheless, at least three different groups of actors should be recognised. First, as mentioned above, nowadays electricity consumers have already reasonably more power to influence their energy costs through informed selection of electricity retailer and tariff plan, energy efficiency measures and even participation in various demand response programs, albeit, with unreasonable difficulties. Second, operators of demand response mechanisms / aggregators can increase the overall electricity market efficiency by striving to optimize their own techniques. And, finally, policy-makers have significant impact on the operation of the electricity market and they can influence how it affects electricity end-consumers. The research work presented in this Thesis directly concerns two of the groups of actors mentioned – demand response mechanisms / aggregators and policy-makers. For the former, methods and algorithms to optimize their participation in an electricity spot market have been proposed. For the latter, decision support is realized in the form of assessment and recommendations in regard to the influence realization of new business models – aggregator entrepreneurship on the electricity market and, subsequently, the options to support it. A common feature of these topics is the aim – the maximization of the social welfare, albeit from different perspectives. Despite the fact that the movement of prosumers in Latvia is at an early stage of development, active electricity consumers / prosumers' awareness also were addressed.

In the modern world, everything is connected – as one industry changes, so do others and the chain continue to infinity. The energy field also does not stand still. Not only technology and new role of consumer, but also new business models in the energy sector are developing.[11] Regardless, the process of these changes, the Baltic energy systems have only partially achieved their development goals: emissions are still overall high, and the Baltic energy system as a whole has become acutely deficient. In 2020, local power plants generated only 55 % of the consumed electricity. [12] To solve the problem of generation shortage, significant capacities of renewable energy power plants will be required in the near future. This challenge is compounded by the fact that an increase in electricity consumption in transport, households and industry is expected. In this regard, the author undertakes a serious task to investigate the problem of demand response for renewable integration and consumer engagement. As a problem, it has been solved yet neither in theory nor in practice in Latvia, which emphasises

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[11] Stecenko, I., Silinevicha, V., Viskuba K. 2020. Political, Economic, Social and Technological Perspectives of Aggregator of Demand Response for Renewable Integration, Acta STING, vol 4, Brno. 16–32, e-ISSN 1805-6873. [Accessed: 22.09.2020]

[12] *Ibid*.

the **importance** of the chosen theme. The difficulty of solving the problem lies not only in the lack of experience as such in Latvia, but also in the fact that it is connected with the maximization of the social welfare. The price of electricity affects nearly all facets of a nation's economy, from gross domestic product, all the way down to an individual household's standard of living. Energy is an essential element in the production of nearly all goods and services, therefore energy prices have a ripple effect to the general level of prices for the country as a whole. Able to quickly balance demand and supply, demand response management also can decrease wholesale electricity prices, which then leads to lower retail prices as well. The author, using regional economics, economic and mathematical tools and methodologies, as the main sciences of research, suggests the solution of the problem of demand response for renewable integration and consumer engagement and application of econometric methods allows expanding the essence of regional economics as a part of applied economics. In addition, this aspect emphasises the interdisciplinary connection with the other economic disciplines.

The problem and peculiarities of Demand Response Mechanism development in Latvia has not been widely considered in publications of Latvian scientists from this point of view, which confirms the relevance of the given research.

The degree of development of the research theme

The comprehensive studies of peculiarities of energy sector are well developed in Latvia. Their results are used for the elaboration of the Latvia's National Energy and Climate plan (NECP) 2021–2030[13] (one of the main energy planning documents in Latvia). Its long-term objective is climate-neutral economy by improving energy security and the well-being of society in a sustainable, competitive, cost-effective, secure, and market-based manner. The following r experts and scholars greatly contributed to the development of these documents: A. Blumberga, G. Bažbauers, D. Blumberga, D. Jauzems, D. Slišāne, V. Priedniece and others. Vast number of scientists contributed to investigation and academic research in investigating and assessing economic potential for Demand Response (DR), the role of aggregators in the energy transition under the latest European regulatory framework, possibilities of Latvian households' potential participation in the energy market as prosumers. Among them are following scientists: A. Sauhats, M. Balodis, R. Varfolomejeva, N. Sokolovs, H. Coban, K. Baltputnis, Z. Broka, M. Rubins, I. Pilvere, O. Linkevics, R. Petrichenko, L. Sadoviča, G.

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[13] National Energy and Climate Plan of Latvia 2021–2030. 2018. For Submiting to the European Commission for Evaluation Latvian Ministry of Economy.Riga,.Available online: https://ec.europa.eu/energy/sites/ener/files/documents/ec_courtesy_translation_lv_necpdf [Accessed: 14.03.2020]

Junghāns, A. Krumins, A. Tamane, E. Dzelzitis, D. Lauka, A. Barisa, P. Shipkovs, K. Lebedeva, L. Migla, G. Kashkarova and others.

R. Moura, M. C. Brito address concepts of consumer aggregation, but does not include any recent European regulatory framework, such as the Clean Energy for all Europeans Package (CEEP), however they present some business model case studies of DR for transport industry. Okur et al., Lu et al., Stede et al., Burger et al. in their comprehensive investigations offer extensive classification on concurrent literature on aggregator strategies, however, the assessed strategies are not directly linked to the different possible aggregator models, missing an aggregator taxonomy for business models.

The aim of the Thesis

The aim of the Thesis is to develop the conceptual framework of the electricity Demand Response for renewable integration and consumer engagement, based on the Demand Response aggregator that is by itself an information and technological company in electricity sector of Latvia.

Objectives of the Thesis

1. Based on the analysis and synThesis of scientific literature to compare definitions and approaches related to the electricity Demand Side Management and to provide a theoretical framework for defining the Demand Response for market of electricity as well as to study the impact of the economic and institutional environment of the Demand Response in the electricity market and-integration of renewable sources;
2. To develop a model for implementation of the concept of regional Demand Response aggregator, that will allow to solve the problem of reducing electricity consumption and the choice of active consumers to be switched off for the current hour if the amount of electricity is not enough, even taking into account a decrease in its consumption;
3. To identify and examine the trends of physical indicators of the energy industry, renewable energy and system prices of electricity, approximate formulae dependencies and the coefficients of determination;
4. To develop a methodology for a comprehensive analysis of correlation and regression dependencies of an electricity sector physical and system price indicators, based on the adaptation of the corresponding classical mathematical models;

5. To analyse the consumer behaviour, based on the Demand Response, carrying out quantitative research of prosumers in Latvia;
6. To develop and suggest a new advanced model of the bi-level optimisation technique of the balance of supply and demand, where on the first stage it is proposed to solve the problem of reducing electricity consumption and, at the second stage – to solve the optimization problem of determination of temporarily disconnected user groups in response to electricity market prices, to devise and, based on case studies, validate a method for the optimized model.

Hypotheses of the Thesis

The development of electricity Demand Response Mechanism strategies for renewable integration and consumer engagement in Latvia can be based on the application of regional demand response aggregator – an information and technological company, in electricity sector of Latvia.

Research object

The Demand Response Mechanism in the energy sector.

Research subject

Demand Response services in Latvia, that impact the implementation of a technology of Demand Response aggregator.

Novelty of the Thesis

The most important scientific results obtained by the author are follows:

1. Definitions and approaches related to the electricity demand side management have been improved and a theoretical framework for defining the Demand Response for market of electricity have been developed.
2. The impact of the economic and institutional environment factors of the Demand Response in the electricity market and integration of renewable sources has been categorised.
3. The trends in macroeconomic and physical indicators of the energy industry, renewable energy and a system price of electricity, approximate formulae of dependencies and the coefficients of determination have been identified.

4. A new methodology for a comprehensive analysis of correlation and regression dependencies of an electricity sector physical and system price indicators, based on the adaptation of the corresponding classical mathematical models, has been developed, which adds to the literature on state support impact on the electricity market.
5. A new model of the bi-level optimization technique of the balance of supply and demand, developed and substantiated where on the first stage it is proposed to solve the problem of reducing electricity consumption and, at the second stage – to solve the optimization problem of what groups of active consumers loads should be shifted off, if the amount of electricity is not enough and, therefore, in response to electricity market prices.
6. Based on the new model, the "Regional Aggregator", which is an information and technological company, in electricity sector of Latvia is developed.

The Practical value of the Thesis

The scientific results obtained by the author are valuable for practical application in development of long-term national strategies and plans for energy industry, with the emphasis on renewable energy sources deployment and active involvement of electricity end-users. The methods developed by the author can help entrepreneurs to effectively implement their business projects within the frameworks of energy sector in the Latvia and other EU member states.

Methods of the research

The research methodology was based on the systemic and dialectical analyses. At different stages of the research and depending on the nature of the tasks, different research methods were applied.

The research of the Thesis is based on:

- monographic-descriptive method**:** content analysis of the literature on the chosen research topic, the comparative analysis and synThesis of scientific literature, research results and reports, analysis of legal acts of the EU and of the Republic of Latvia related to the relevant problems of presented in scientific publications and other academic sources, materials of scientific conferences and seminars, Internet resources (applied in Chapters 1 and 2);
- retrospective analysis of the development of the Electricity Demand Side Management in the Context of the Renewable Energy Integration;

- qualitative research methods, including gathering of information, processing and analysis of qualitative data, interviews of experts, case-study analysis, author's observations;
- quantitative research methods (the survey of potential consumers and results of surveys and interviews carried out by the author, using the tool developed by the author, comparative analysis of empirical data by using central trends or location and variation indices, grouping and analysis of ratios (applied in Chapter 3);
- The statistical method: methods of statistical and econometric analysis employed for assessing the dynamic of absolute and relative indicators, identifying their relationships, formulation of equations and identifying the trends in indicators for given period of observation, published statistical data of the Central Statistical Bureau applied in Chapter 3);
- The modelling research method: the method of theory of operations investigation for the formulation and solution of the problem of combinatorial optimization of the balance of supply and demand of electricity (applied in Chapter 4).

The implementation of each phase resulted in intermediate results of the study (data collections, data tables and figures, summaries of information, analysis, evaluations, etc.), that formed the basis to launch and develop the next phase of research. That is – each subsequent phase of the study implementation was based on the interim results of the previous phase of the study.

Limitations of the Research

This Thesis focuses on the electricity day-ahead market in the Nord Pool region. The physical parameters used in this Thesis are specific for the region. Thus, some adjustments will be needed if one wants to apply the results from this Thesis to different markets and areas. Demand and supply of electricity, and consequently system electricity prices in Latvia are determined by various factors, such as fuel structure, cross-border interconnections, markets interconnection, renewable energy, concentration of market suppliers, weather conditions, etc. Nevertheless, this Thesis focuses only on some of them. The technical aspects are discussed in this Thesis to some extent. They are undoubtedly important aspects for this study as an electricity market will develop only if it is technically feasible. However, this Thesis will not propose detailed technical solutions for future scenarios of integration of Demand Response mechanism since this Thesis will focus more on how Demand Response mechanism could be implemented as Demand Response Regional Aggregator. The author analyses the electricity day-ahead market data for the period 2014–2019, part of data for the 2020. Economic data for the 2020 and 2021 were not analysed owing to their limited availability and the impact of COVID-19 pandemic.

Time and Regional Framework of the Research

Calculation of trends of indicators, approximating formulae dependencies and the coefficients of determination for the relevant diagrams and charts are based on big data collected from the Latvian transmission system operator (Augstsprieguma tīkls), Central Statistical Bureau of Latvia, European Network of Transmission System Operators for Electricity ('ENTSO-E'), and Nord Pool the power exchange. The data used in the empirical study is collected from hourly data from the period 1 January 2014 to 31 December 2019, and partly data for year 2020.

Theses for Defence

The following main theses are presented for defence:

1. The development of scientific research in the field of demand management for electricity consumption is influenced by both external factors in relation to the electric power industry, such as economic crises, the spread of information technologies, and internal factors, such as the development of energy markets, the development of technologies for distributed and renewable energy sources, the emergence of new technological trends, an activation of electricity consumers and prosumers.
2. The provision of a demand response – aggregator services should be based on the author’s research methodology for a comprehensive analysis of correlation and regression dependencies of an electricity sector physical and price indicators, based on the adaptation of the corresponding classical mathematical models.
3. The development of the company “Regional Aggregator” should be based on the author’s devised and applied bi-level optimization technique of the balance of supply and demand.

The evaluation of the research results

Theoretical and practical provisions of the Thesis have found the reflection in the publication of eight scientific articles and reports at the eleven international scientific and practical conferences and seminars.

Structure of Thesis

The Thesis structure is determined by the aim, objectives and logic of research. The Thesis includes abstract, introduction, four chapters, conclusions, recommendations and references.

The introduction determines the relevance of the topic of research of the Thesis. The hypothesis, the aim and objectives of the research are determined, as well as the research subject and object, scientific novelty and practical significance, as well as the review of the literature, examined sources and used scientific methods is given.

In the first chapter, the author analyses the theoretical, methodological foundations of the peculiarities in Demand Response for electricity sector.

In the second chapter, economic and institutional environments have been studied, including electricity market liberalization in the EU countries. Attention was given to electricity price factors. Regional framework of the Demand Response has been assessed.

In the third chapter, the author represents the reasoned analysis of the trends of macroeconomics and physical indicators of the energy industry, renewable energy and system prices of electricity, approximate formulae dependencies and the coefficients of determination; there has been devised a methodology for a comprehensive analysis of correlation and regression dependencies of an electricity sector physical and system price indicators, based on the adaptation of the corresponding classical mathematical models, it adds to the literature on state support impact on the electricity market.

In the fourth chapter, the author has put forward, developed and substantiated a new model of the bi-level optimization technique of the balance of supply and demand, were on the first stage it is proposed to solve the problem of reducing electricity consumption and, at the second stage – to solve the optimization problem of what groups of active consumers loads should be shifted off, if the amount of electricity is not enough and, therefore, in response to electricity market prices.

Finally, the conclusions and recommendations are formulated.

The total volume of the promotional work is 160 pages without appendices, 48 tables, 31 figures and 2 Annexes. Bibliography comprises 137 sources.

1 Electricity Demand Side Management in the Contex of the Renewable Energy Integration: Theoretical Framework

The energy industry all around the world is currently undergoing changes due to the development of new technologies, user requirements and restrictions on the availability of natural resources, which are stimulating companies to expand and revise their business, offer new services and open up new markets. Increasing global demand for energy, limited supplies of fossil fuels, as well as environmental pollution and the threat of global climate change[14] have led to increased interest in renewable energy sources. The use of renewable energy sources is considered a key element of energy policy, reducing dependence on fuel imported from third countries, reducing emissions from fossil fuels and decoupling energy costs from oil prices[15].

In the modern world, all industries are connected – as one industry changes, so do others, and the chain continues to infinity. The energy field also does not stand still. Not only technology but also business models in the energy sector are developing. This part of the Thesis, in order to achieve the aim, set in the work, presents the different definitions of Demand Response and its end users – prosumer / active customer / renewable self-consumer, discusses the concept of Demand Response Aggregator, and analyses its role in the EU energy market, reveals the peculiarities of the renewable energy prosumer. First, the author investigates the EU legislation on the subject of terminology and different definitions, then, continues with the academic literature on energy.

1.1 Genesis of the Demand Response concept

Currently, the energy industry in the EU countries, as well as around the world, is undergoing a transformation in which consumers use, store or sell their own electricity or participate in Demand Management (DM) and energy efficiency schemes, thus transforming themselves into active consumers. At the same time, the number of active consumers of electricity (industrial, commercial, agricultural and household consumers) under DM conditions should become quite massive.[16] The Electric Power Research Institute (EPRI)

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[14] Brown, T., Newell, S., Spees, K., Oates, D. 2015. *International Review of Demand Response Mechanisms*; The Brattle Group Inc.: Sydney, Australia, [Online]. Available at: http://files.brattle.com/system/publications/pdfs/000/005/220/original/aemc_report.pdf?1448478639 [Accessed 28.07.2020]

[15] Bird, L. Milligan, M., Lew, D. 2013. *Integrating Variable Renewable Energy: Challenges and Solutions; National Renewable Energy Laboratory*: Golden, CO, USA. [Online]. Available at: https://www.nrel.gov/docs/fy13osti/60451.pdf [Accessed 28.07.2020].

[16] Stede, J., Arnold, K., Dufter, C., Holtz G., Roon S. von, Richstein J. C. 2020. The role of aggregators in facilitating industrial demand response: Evidence from Germany, Energy Policy, Volume 147, 111893, ISSN 0301-4215, https://doi.org/10.1016/j.enpol.2020.111893. [Accessed 17.12.2020] (https://www.sciencedirect.com/science/article/pii/S030142152030608X)

introduced the term DM in the 1980s.[17] From the grid operator perspective, the DM measures substantially minimize activating the number of expensive peaking generating plants. Voluntary optimization of electricity consumption by the end user with a certain economic benefit[18] is carried out by the Demand Response (DR) mechanism. Note that with the development of electricity markets, there was a gradual shift in terminology[19] and the term Demand Side Response (DSR) began to be replaced by the term Demand response. However, despite constant terminological shifts, the terms Demand-side response and Demand Side Management are often used interchangeably. However, across multiple sources, DSR is a specific form of demand management that focuses on load bias aspects rather than the aggregate effect of unit demand reduction. Also, with the development of electricity markets and distributed power supply sources, the term DSM in some sources began to be replaced by the term DSI (Demand Side Integration).

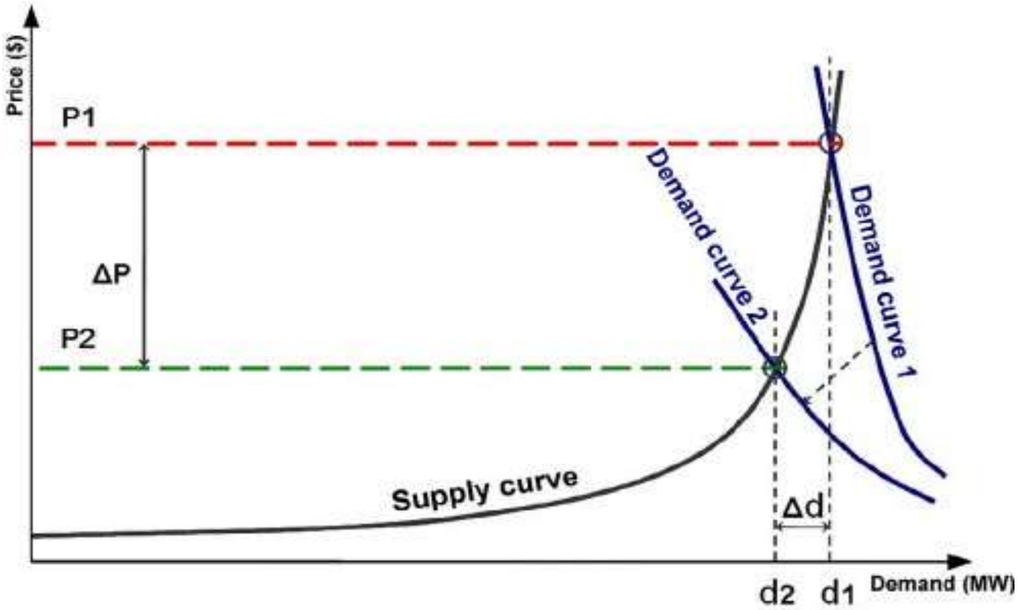

Figure 1.1 **Effect of demand variation on the electricity price**[20]

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[17] Electric Power Research Institute, http://eprijournal.com/wp-content/uploads/2016/01/1980-Journal-No.-3.pdf [Accessed 12.04.2020]

[18] An incentive is a cost or benefit that motivates a decision or action by end-user customers, businesses, or other commercial and regulated parties. Incentives aim to provide value for money and contribute to reaching set objectives. These can be created temporarily (short term) or to support long term strategies. Incentives could be targeted on specific consumer groups, on regulated entities (e.g. grid operator), or on non-regulated entities (commercial market parties). – Smart Grid Task Force, Regulatory Recommendation Report, January, 2015. [Accessed 04.07.2019]

[19] Lampropoulos, L. 2013. History of demand side management and classification of demand response control schemes / I. Lampropoulos, W.L. Kling, F. Ribeiro // Power and Energy Society General Meeting (PES). 173–178. DOI: 10.1109/PESMG.2013.6672715. [Accessed 07.10.2019]

[20] Teimourzadeh Baboli, Payam & Eghbal, Mehdi & Moghaddam, M. & Aalami, H. 2012. Customer behavior based demand response model. Proc. IEEE Power & Energy Society General Meeting (PES '12). 1–7. 10.1109/PESGM.2012.6345101. [Accessed 11.08.2020]

Figure 1.1 presents some of the major DR benefits that may be achieved if the DR-capable loads optimize energy consumption. The author also notes, that DM resources are also available in the retail electricity market, when, when it is scarce in the Active Customer (AC) region, consumption is reduced. According to the Gellings[21], there is a significant scope for DSM to contribute in increasing the efficiency and use of system assets. Demand side management has been considered since the early 1980s. It can be used as a tool to accomplish different load shaping objectives, such as peak clipping, valley filling, load shifting, strategic conservation, strategic load growth and flexible load shape (see Figure 1.2). Currently consumers have no means of receiving information that would reflect the state of the grid thus cannot react to reach the balance and increase efficiency. Due to the nature of renewable, it is not possible to control or request power when it is needed. The main objectives of DR techniques are reduction of peak load and the ability to control consumption according to generation[22]. Usually, end-users have very little practical knowledge about their flexibility and are unaware of their usage patterns and behaviour. Hence, participants in DR programs show a lower response than the expected levels. Aggregators analyse end-users' flexibility and advertise financial benefits to engage end-users. According to[23]: "Aggregator: a demand service provider that combines multiple short-duration consumer loads for sale or auction in organised energy markets". Also defined as "a market participant that combines multiple customer loads or generated electricity for sale, for purchase or auction in any organised energy market"[24]. The aggregator categorizes the end-users into different groups based on the user's interval energy consumption and usage characteristics, such as the type of appliances used and their DR flexibility, level of involvement, and so forth.

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[21] Gellings, C. W. 1985. The concept of demand-side management for electric utilities, Proceedings of the IEEE, 73 (10), 1468–1470 CrossRef

[22] Gelazanskas, L., Gamage K. A. A. 2014. Demand side management in smart grid: A review and proposals for future direction, Elsevier, Sustainable Cities and Society, vol. 11, 22–30.

[23] European Commission. (2017a). Third Report on the State of the Energy Union (Communication No. COM (2017) 688 final). https://ec.europa.eu/commission/publications/third-report-state-energy-union_en European Commission. (2017b, February 23). Proposal 2016/380 (COD) for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on common rules for the internal market in electricity. Retrieved from https://ec.europa.eu/transparency/regdoc/rep/1/2016/EN/COM-2016-864-F2-EN-MAIN-PART-1.PDF [Accessed 19.12.2020]

[24] European Commission. (2016b, November 30). Commission proposes new rules for consumer centred clean energy transition. Retrieved from EC Energy News website: https://ec.europa.eu/energy/en/news/commission-proposes-new-rules-consumer-centred-clean-energy-transition [Accessed 17.12.2020]

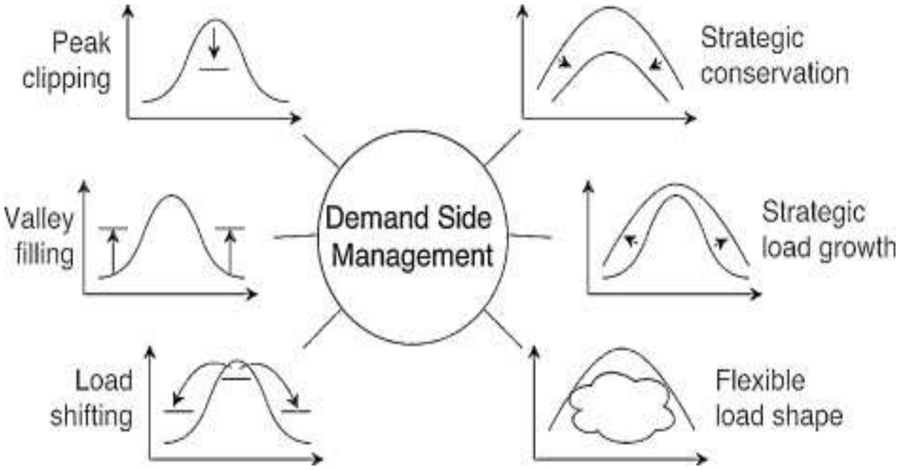

Figure 1.2 **Basic load shaping techniques**[25]

There are three actions a customer can take in response. Customers can reduce load only during critical peak time and maintain normal load pattern during off-peak time. This induces a decrease in customers comfort as they are forced to curtail electricity usage at certain times but reduces the overall consumption thus reducing electricity bill even further. The second action that could be taken in order to respond to high electricity prices or low availability is to offset electricity use from peak to off-peak time. This method would flatten the load shape by both decreasing the peak load and filling low consumption valleys. It does not reduce the average amount of energy used by the end users, but increases the transmission and distribution efficiency as the system operates in more stable mode. Finally, customers can use on site generation to reduce demand seen by the utility. This would increase user autonomy, further decentralise generation and decrease average load on distribution and transmission grids. On the other hand, it would maximise system complexity[26]. DR aggregator should be coordinated with a customer's temporal order of activities and schedules. Notably, the residential customers have some crucial factors that should be duly considered. Deferring household activities and appliances rescheduling sometimes affect dependent activities and should be practically and carefully managed when adopting beneficial technology in a smart grid to improve the grid's functionality[27]. To participate in DR programs, the users must reveal their willingness, preference, in-home activity data, and so forth, which may breach privacy[28].

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[25] Gellings, C. W. 1985. The concept of demand-side management for electric utilities, Proceedings of the IEEE, 73 (10), 1468–1470. CrossRef

[26] Gelazanskas, L., Gamage K.A.A. 2014. Demand side management in smart grid: A review and proposals for future direction, Elsevier, Sustainable Cities and Society, vol. 11, 22–30.

[27] Kim, J. H. and Shcherbakova A. 2011. Common failures of demand response, *Energy*, vol. 36, no.2, 873–880.

[28] Lisovich, M. A., Mulligan, D. K., and Wicker, S. B. 2010.Inferring personal information from demand-response systems, *IEEE Secur. Priv.*, vol. 8, no. 1, 11–20.

DR programs, in turn, are classified into two basic directions: system rationing of electricity consumption and economic rationing of electricity consumption. System rationing of electricity consumption (incentive-based programs or system led programs) – a system for managing the demand for electricity, based on systemic restrictions on the electricity consumption of electricity consumers during peak periods of the power system, aimed to elimination of the growth of power consumption load. System rationing, as a rule, is applied during periods of emergency loads in the power system. Also, system rationing is referred to the category of "explicit" demand management mechanism, which is associated with a direct impact on consumer demand within specific periods and on the competitive value of demand. Economic regulation of electricity consumption (price-based programs or market-led programs) – a demand management system for electricity consumption based on price incentives of electricity consumers to manage their own electricity consumption.

Price incentives offer electricity consumers a lower unit cost of electricity consumption in exchange for a reduction in electricity consumption from the grid during peak periods[29], and conversely, consumers, those who do not reduce their own consumption during peak periods of the power system will pay for electricity at higher tariffs. Also, economic rationing is classified as an "implicit" mechanism demand management, which is due to the lack of concretization in the periods and values of the decrease in demand for electricity consumption by consumers and the dependence on the personal desire of the consumer to reduce the load in a certain period of time.

The Price-based Control[30],[31] tool is based on three tariff categories:

a) static differentiated tariffs – electricity tariffs differentiated by time periods within a day and having fixed values within periods;
b) dynamic tariffs – electricity tariffs differentiated by time periods within a day and having variable values within periods;
c) real-time tariffs – electricity tariffs formed through the market pricing mechanism and depending on the ratio between supply and demand parameters at a certain point in time.

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[29] Grainger, G. H. 1976. A practical approach to peak-load pricing / G.H. Grainger // Public Utilities Fortnightly. Vol. 98, № 6, 19–23.

[30] Haider, T. H. 2016. A review of residential demand response of smart grid / Haider, T. H., See, O. H., Elmenreich, W. // Renewable and Sustainable Energy Reviews. 166–178 DOI: 10.1016/j.rser.2016.01.016. [Accessed 17.12.2020]

[31] Hussein J. J., Jiashen T., Dahaman I., and Hamza A. 2018. Impacts of Demand-Side Management on Electrical Power Systems: A Review Energies 11, no. 5: 1050. https://doi.org/10.3390/en11051050

The classification and comparison of the types of Demand Response programs are summarized in Table 1.1. A number of studies[32],[33] are devoted to the study of the influence of changes in electricity prices on the parameters of changes in demand for electricity. The analysis of various tools for managing the demand for electricity consumption, as well as functioning demand management programs in the different countries, allows us to state a significant differentiation and specificity of such tools and programs lies in the country context. It is important to note that the Demand Response programs shown in Table 1.1 are not interchangeable and all of these mechanisms can be used in a complex.

Table 1.1 shows the systematization of the used programs in different countries, implemented according to a number of criteria. The first is the nature of the use of demand management programs, which is constant and extreme. Extreme – in demand management during emergency periods of the functioning of the power system, and the constant one is aimed at daily equalization of the unevenness of the demand for electricity in the power system. The second criterion is the category of consumers, the third is the level of implementation of programs in each country, which reflects the degree of integration of demand management programs into the daily activities of electricity consumers. Although DSM programs are widespread in most countries of the European Union, in some countries, such like Latvia and Estonia, DSM programs are only at the concept stage.

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[32] Bernard, J. T. 2011. A pseudo-panel data model of household electricity demand / J.T. Bernard, D. Bolduc, N.D. Yameogo // Resource and Energy Economics. 315–325. DOI: 10.1016/j.reseneeco.2010.07.002. [Accessed 21.12.2020]

[33] Kamerschen, D. 2004. The demand for residential, industrial and total electricity, 1973-1998 / D.R. Kamerschen, D.V. Porter // Energy Economics. 87–100. DOI: 10.1016/S0140-9883(03)00033-1. [Accessed 17.12.2020]

Table 1.1

The classification and comparison of the types of Demand Response programs
(made by the author, based on[34],[35],[36],[37],[38])

No	Name of DR programme	Standart type	Tariff type	Advantage of the program	Disadvantages of the program
1	Interruptible Programmes	incentive-based programs	Fixed	To receive a discount, a load interruption is required for a short time	The need to transfer or reduce the load on required time
2	Direct load control Programmes	incentive-based programs	Fixed	The possibility of obtaining a significant discount due to reduce the load	The consumer must reliably execute the commands of the system operator
3	Emergency DR Programmes	incentive-based programs	Fixed	The possibility of obtaining a significant discount due to operational load reduction	The need to transfer or reduce the load on required time
4	Demand bidding	incentive-based programs	Variable	The possibility of obtaining a significant discount due to reduced load	The need to transfer or reduce the load on required time
5	Capacity Market	incentive-based programs	Variable	The possibility of obtaining a discount due to the exposure of the accepted commitments	The need to transfer or reduce the load on required time
6	Ancillary Services	incentive-based programs	Variable	Possibility of obtaining discounts due to exposure commitments made	The need to transfer or reduce the load on required time
7	Time of Use (ToU)	–	Variable	During peak periods, you can shift the load to minimize costs	The consumer should closely monitor the change time
8	Critical Peak Pricing (CPP)	–	Fixed	To get a discount, you should reduce the load only for a short time	The need to quickly reduce demand
9	Real Time Pricing (RTP)	–	Variable	The client can change the price of electricity purchases in depending on the period	The need for operational control and demand reduction

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[34] Delgado, R. M. 1985. Demand-side management alternatives / R. M. Delgado // Proc. of the IEEE. Vol. 73. JOP 6363 [Accessed 17.12.2019]

[35] Lampropoulos, I. 2012. Analysis of the market-based service provision for operating reserves in the Netherlands / I. Lampropoulos, J. Frunt, A. Virag, F. Nobel, J. van den Bosch, and W.L. Kling // Proc. of the 9th International Conference on the European Energy Market. 1–8. DOI: 10.1109/EEM.2012.6254735. [Accessed 11.12.2019]

[36] Lampropoulos, L. 2013. History of demand side management and classification of demand response control schemes / I. Lampropoulos, W.L. Kling, F. Ribeiro // Power and Energy Society General Meeting (PES). 173–178. DOI: 10.1109/PESMG.2013.6672715. [Accessed 17.12.2019]

[37] Steiner, O. 1957. Peak Loads and Efficient Pricing / O. Steiner // The Quarterly Journal of Economics. Oxford University Press. Vol. 71, № 4. 585–610.

[38] Torriti, J. 2010. Demand response experience in Europe: Policies, programmes and implementation / J. Torriti, M. G. Hassan, M. Leach // Energy. Vol. 35, Issue 4. 1575–1583. DOI: 10.1016/j.energy. 2009.05.021. [Accessed 15.12.2019]

It is necessary to use the full range of available demand management resources and cover all categories of consumers for whom it is possible to benefit from management own load. Demand management programs in an individual country are developed taking into account the specifics of the demand for electricity consumption, the structure of demand for electricity consumption by consumers, the level the introduction of information technologies, as well as the importance of the task of increasing energy efficiency for economy.

Summarising, due to the nature of renewable, it is not possible to control or request power when it is needed. The main objectives of DR techniques are reduction of peak load and the ability to control consumption according to generation. Usually, end-users have very little practical knowledge about their flexibility and are unaware of their usage patterns and behaviour. Hence, participants in DR programs show a lower response than the expected levels.

Recent decades have seen a strong trend towards the integration of renewable distribution generation systems into the grid, and advanced management strategies have been developed to ensure reliable, flexible, economical, and sustainable operations.[39] Increase in load demand at a rate not proportionate to the available generation and transmission capacity will compromise system reliability and resiliency. Hence, for intermittent RE generation to augment these problems, optimal energy management schemes are required. In recent years, a popular methodology used to balance supply and demand on the grid, particularly during times of peak load demand, is achieved by changing the demand pattern rather than increasing the supply; this practice is known as "demand response".[40]

Demand management can significantly affect electricity prices, reduce the need for the construction of generating and network capacities, promote the integration of renewable energy and electric transport, maximize the effect of the introduction on the consumer side of such innovative digital technologies as the Internet of Things, Smart Home. However, in order to obtain such benefits, Demand Management for electricity must become sufficiently widespread through the participation of a sufficient number of industrial, commercial, agricultural and residential consumers.

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[39] Güner, S., Erenocglu, A. K., ¸Sengör, ˙I., Erdinç, O., Catalão, J. 2020. Effects of on-site pv generation and residential demand response on distribution system reliability. Appl. Sci., 10, 7062. [CrossRef] [Accessed 19.01.2020]

[40] Conteh, A., Lotfy, M. E., Kipngetich, K. M., Senjyu, T., Mandal P., Chakraborty, S. 2019. An Economic Analysis of Demand Side Management Considering Interruptible Load and Renewable Energy Integration: A Case Study of Freetown Sierra Leone. *Sustainability*, 2019 *11*, 2828. https://doi.org/10.3390/su11102828 [Accessed 12.02.2019]

The demand management mechanism implies a voluntary reduction in electricity consumption by the end user, in particular, during periods of peak prices in the wholesale market, with an economic benefit for such a decrease[41]. However, demand management resources, and significant ones, are also available in the retail market. In world practice, the main solution for involving consumers in the retail market in demand management has become the creation of specialized organizations – demand management aggregators.

From the author's point of view, in disclosing the cause-and-effect relationships of the development of world research in the field of demand management, it is advisable to single out 6 main stages, at each of which urgent scientific problems of its time are solved and at the same time the prerequisites for the emergence of objective tasks of the following period are formed:

Stage 1 – identification of the problem of demand volatility, systematization of knowledge about the mechanisms in the field of demand volatility management (1971–1980);

Stage 2 – the beginning of the implementation of electricity demand management in the form of programs (1980–1994);

Stage 3 – development and implementation of electricity demand management programs in various countries of the world (1994-2004);

Stage 4 – integration of demand management models into the system of electricity markets (2004-2009);

Stage 5 – integration of energy demand management technologies with the Smart Grid concept (2009–2014);

Stage 6 – the introduction of distributed energy technologies, renewable energy, electric vehicles and the Internet of Things (2014 – present).

One of the prerequisites for the development of research in the field of electrical load management was the development of technical means for monitoring, collecting, processing and transmitting data on the parameters of electricity consumption, which fell on the beginning of the 1970s. Thus, in the studies of K. Jacobs[42] , Spencer[43] , Eldridge[44] in 1971, proposed electricity metering technologies, allowing to perform both discrete and automatic remote reading of instrument readings, and in 1973, directions were proposed for improving measurement technologies and modernizing metering devices in order to participate in

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[41] Bird, L. Milligan, M., Lew, D. 2013. *Integrating Variable Renewable Energy: Challenges and Solutions; National Renewable Energy Laboratory*: Golden, CO, USA, [Online]. Available at: https://www.nrel.gov/docs/fy13osti/60451.pdf [Accessed 28.07.2019].

[42] Jacobs, K. 1971. Prepare now. Automatic remote meter reading is coming / K. Jacobs // EZec. Lightandpower. 49.

[43] Spencer, J. H. 1971. Automatic meter reading-1971 / J.H. Spencer // In Proc. of the Amer. Power Conf. Vol. 33. 962–969.

[44] Eldridge, F. R. 1971. System for automatic reading of utility meters / F.R. Eldridge // MITRE Re M72-1. 57–62.

managing the demand for electricity consumption[45]. In general, the work of this first stage can be built in a certain logical sequence from the identification of the load management problem to the use of various data collection technologies to solve this problem. And, as a consequence, to the development of specific mechanisms of demand management and the assessment of cost characteristics and efficiency of management impacts. Kaplan[46] and Beaty[47] suggested application bidirectional systems for managing loads of electricity consumers. In the works of Hastings[48] and Stocker[49], published in 1979, the results of a study of the effectiveness of the use of remote load control systems for domestic water heaters and air conditioners are presented.

A separate part of the research is devoted to the issue of modelling scenarios of changes in electrical loads during control Berg[50], Schweiser[51], Bossert[52], Preiss[53]. The scientific developments in the field of load management, modelling of various scenarios of power consumption and the use of modern methods of collecting and processing information for this purpose has resulted in the emergence of studies devoted to the analysis of the impact of the implemented measures on the cost of energy resources and the assessment of the results of approbation and the level of efficiency of technologies for managing the demand for power consumption. The logical continuation of scientific developments on the implementation of demand management mechanisms has become research on the testing and effectiveness of new technologies. In the works of Walker[54], A. Requin and Largo[55] assesses the effectiveness of the application of flexible tariffs for the supply of electricity within the energy sector of United

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[45] Eldridge, F. R. 1973.Automatic Meter Reading Via Cable / F.R. Eldridge // IEEE Power Engineering Society. Winter Meeting. Paper № C73 069-2. 72–75.

[46] Kaplan, G. 1977. Two Way Communication for Load Management / G. Kaplan // IEEE Spectrum. 47–50.

[47] Beaty, H. W. 1977. Automated distribution improves system operations and reliability / H.W. Beaty // Elec. World. Vol. 188. № 2. 39–50.

[48] Hastings, B. F. 1979. Ten Years of Operating Experience with a Remote-Controlled Water Heater Load Management System at Detroit Edison / B.F. Hastings // IEEE Power Engineering Society Summer Meeting. Vol.: PAS-99. 1437– 1441.

[49] Stocker, D. V. 1979. Load Management Study of Simulated Control of Residential Control Air Conditioners on the Detroit Edison Company Systems / D.V. Stocker // IEEE Power Engineering Society Summer Meeting. Vol. PAS-99. 1616–1624.

[50] Berg, G.J. 1979. Model representation of power system loads / G.J. Berg, A.K. Kor // PICA Conf. Proc. 153–162.

[51] Schweizer, F. 1975. A computer model for investigating optimum off-peak uses of electric power / F. Schweizer // Westinghouse Research Laboratories. Research re 75-1C55-ENERGY-Rl. Pittsburgh. 73–78.

[52] Bossert, R. W. 1977. Defining time-of-use periods for electric rates / R.W. Bossert // Public Utilities Fortn&htly. Vol. 99. – № 7. 19–24.

[53] Preiss, R. F. 1978. Impact of voltage reduction on energy and demand / R.F. Preiss, V.J. Warnock // Presented at the IEEE Winter Power Meeting. New York. 27–30.

[54] Walker, D. 1977. Design of Electricity Tariffs in England and Wales and Experience in their Application / D. Walker // Energy Systems Forecasting, Planning and Pricing. 92–98.

[55] Requin, A. 1974. Experiences with French Tariff Structures: Technical Means for the Implementation of Tariff Structures / A. Requin, J. Lorgeau // Energy Systems 462 Forecasting, Planning and Pricing. Eds., Proc. of a French American Conf., Univ. Wisconsin-Madison. 285–326.

Kingdom and France. These studies became the basis for the development of the issue of applying flexible tariffs for the supplied electricity and were subsequently continued by Mitchell[56][57], Jefferson[58], Malko[59]. In addition, in 1979, one of the first studies appeared devoted to the analysis of the application of DSM elements in the practical activities of enterprises using the example of the USA company – the electricity supplier Minnkota Load Cooperative[60]. Thus, it laid the foundation for research in the field of demand management for electricity consumption, analysed the possibilities of direct and indirect control of consumer behaviour, as well as the feasibility of using economic incentives. The formed theoretical platform became the basis for the development of specific demand management programs and recommendations for their implementation, taking into account industry-specific, social and economic country characteristics, which became the main prerequisite for the transition to the next qualitatively new stage of scientific research.

The next stage in the development of research in the field of demand management is characterised by the beginning of the practical implementation of the theoretical results of research in the field of demand management in development programs for electricity companies operating in the power systems of the United States and Europe[61]. As a result of the introduction of practical DSM tools into the operation of the power systems of the United States and European countries, price incentives and penalties for exceeding electrical loads began to be applied to end-users of electricity, aimed at levelling the growth and volatility of demand in the power systems. This determined the beginning of an era when not only energy companies began to participate in load management of power systems, but also consumers of electricity, including household. The latter became a prerequisite for the development of scientific research in the field of modelling and control of own electrical loads of various types of electricity consumers, in both industrial and the household sector. Another essential prerequisite for the

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[56] Mitchell, B. M. 2013. Peak-Load Pricing in Selected European Electric Utilities / B. M. Mitchell, J. Acton // R-2031-DN RAND Corporation. Santa Monica. CA. – 1977. – 25–32. Lampropoulos, L. History of demand side management and classification of demand response control schemes / I. Lampropoulos, W.L. Kling, F. Ribeiro // Power and Energy Society General Meeting (PES). 173–178. DOI: 10.1109/PESMG.2013.6672715. [Accessed 10.12.2019]

[57] Mitchell, B. M. 1977. Electricity pricing and load management: foreign experience and California opportunities / B.M. Mitchell, W.G. Manning, Jr., J. Acton // R-2 IOLCERCDC. RAND Corporation. 112–117. 440. Mitchell, B.M. 1977. Peak-Load Pricing in Selected European Electric Utilities / B.M. Mitchell, J. Acton // R-2031-DN RAND Corporation. Santa Monica. CA. 25–32.

[58] Jefferson, W. J. 1977. Time-differentiated rates and the real world / W.J. Jefferson // Elec. World. № 9. 116–120.

[59] Malko, J. R. 1978. Implementing time-of-use rates / J. R. Malko // Paper presented at Program of Engineering Economy for Public Utilities. Stanford Univ. 211–219.

[60] Nelson, M. D. 1979. Minnkota's Load Management Program: Economic Aspects / M.D. Nelson // IEEE PES Summer Meeting. Paper № F79. 671–679. [Accessed 10.12.2019]

[61] Gellings, C. W. 1981. IEEE PES Load Management Working Group / C.W. Gellings // IEEE Power Engineering Review. Load Management Working Group 452 of the System Planning Subcommittee of the Power Engineering Committee. Vol. PER-1. № 8. 7–8. [Accessed 10.12.2019]

beginning of a new stage in the development of research in the field of DSM was the development of means and technologies of computers, which since the beginning of the 1980s. been applied in all spheres of industry, including energy sector. The involvement of computer technologies in modelling the electrical loads of consumers in various scenarios of demand management made it possible to derive research to a qualitatively new level. As a result of the spread of the use of computer technologies, new mechanisms for managing individual business processes in industry began to appear, among which integrated resource planning models can be distinguished, which subsequently began to be used, including in managing the demand for electricity. In the work of Hobbs[62] in 1993, it was proposed to embed the DSM system in an integrated resource planning system, which simultaneously contributes to an increase in the efficiency of management of both resource potential and the cost of electricity. The application of the technology proposed by Hobbos is still relevant today.

The prerequisites for the formation of the third stage in the development of world research in the field of demand management are mainly based on the positive practical experience gained at the previous stage in USA and European countries. Implementation of DSM technologies in the development programs of energy companies and energy systems in the USA and Europe, development of metering, control and management technologies for electrical loads, as well as the continuing rise in the cost of primary fuel and energy resources on the world energy markets, along with an increase in demand for their consumption, raised the urgency of improving the energy efficiency of electricity consumption and determined the emergence of a new stage of scientific research in the field of demand management. A feature of this stage can be considered the expansion of the geography of research and practical application of DSM technologies to all OECD countries, countries of South America, Oceania, the Middle East and some countries of the Asia-Pacific region. After the start of the International Energy Agency Demand Side Management (IEA DSM) project, organized in 1994 by the International Energy Agency, the implementation of demand management projects began in the first 7. OECD countries: Austria, Denmark, Spain, Korea, the Netherlands, Sweden and the USA[63]. Among the most important studies on the specifics of the implementation of demand management programs in the countries of the world, one can single out the work of M.

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[62] Hobbs, B. F. 1993. Measuring the economic value of demand-side and supply resources in integrated resource planning models / B. F. Hobbs, H. B. Rouse, D. T. Hoog // IEEE Transactions on Power Systems. Vol. 8, Issue: 3. 979–987. DOI: 10.1109/59.260903. [Accessed 10.12.2019]

[63] Vine, E. 1996. International DSM and DSM program evaluation: an INDEEP assessment / E. Vine // Energy. 983–996. DOI: 10.1016/0360- 5442(96)00028-X. [Accessed 11.12.2019]

Campanano[64] on the development of demand management programs in the Philippines. Thomas assessed the role of the demand management program in Great Britain[65]. Bandala[66] and Blank[67] conducted a similar study for Mexico, Fouquet[68] for France. Z. Liu[69] assesses the energy conservation program and DSM in China. In the works of scientists Geller in[70], Hirst[71] and Rosenstock[72] performed an assessment of the limitations and prospects of demand management programs in the United States. Scientific research at this stage is distinguished by their practical orientation and orientation towards considering the specific features of countries in the development and implementation of programs for managing demand for electricity consumption: Seppall[73] – Finland, Gaul[74] – Germany, Shvehdi[75] – Saudi Arabia, Slingerland[76] – Netherlands, Beenstock[77] – Israel, Popovic[78] – Serbia, Bernard[79] – Canada.

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[64] Campanano, M. 1994. Philippine Appliance Efficiency Programme / M. Campanano // Dept of Energy, Philippines Proceedings fi'om Regional Policy Worlchop on Energy Efficiency Standards and Labelling IIEC. 192–199. [Accessed 10.12.2019]

[65] Thomas, C. G. 1994. The role for demand-side management in the UK / C.G. Thomas // IEE Colloquium on Demand-side Management and Resource Planning in the United Kingdom and Europe (Digest No. 1994/186). 11–15.

[66] Bandala, A 1995.Importance of the Mexican lighting systems in commerce and services / A. Bandala // Prepared for the Right Light Three. Anzures, Mexico. 329–345.

[67] Blanc, A. 1995. History and update of residential lighting projects in Mexico / A. Blanc, O. de Buen // Prepared for the Right Light Three Conference. Piso, Mexico. 24–29.

[68] Fouquet, D. 1995. The French DSM Program: An Overview Prepared for the European Council for an Energy Efficiency Economy / D. Fouquet // The Energy Efficiency Challenge for Europe. Summer Study Proceedings, held in Mandelieu, France.

[69] Liu, Z. 1994. Industrial Sector Energy Conservation Programs in the People's Republic' of China during the Seventh Five-Year Plan (1986–1990) / Z. Liu, J. E. Sinton, F. Yang, M. D. Levine, and all // Berkeley. 66.

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[71] Hirst, E. 1996. The future of DSM in a restructured US electricity industry / E. Hirst, R. Cavanagh, Miller // Energy Policy. 303–315. DOI: 10.1016/0301-4215(95)00139-5. [Accessed 10.12.2019]

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[74] Gaul, A. J. 1996. Evolutionary strategies applied for an optimal management of electrical loads / A. J. Gaul, E. Handschin, W. Hoffmann // Proceedings of International Conference on Intelligent System Application to Power Systems. 368–372.

[75] Shwehdi, M. H. 1996. An assessment method for consumer load management / M.H. Shwehdi, A.Z. Khan // Proceedings of 8th Mediterranean Electrotechnical Conference on Industrial Applications in Power Systems, Computer Science and Telecommunications (MELECON 96). 1360–1363.

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The prerequisite for the emergence of the next, fourth, stage of world scientific research in the field of demand management for electricity consumption was the development and implementation of market-based energy systems in many countries. Systemic constraints due to the constant growth of demand, leaps in price in the electricity markets during peak periods, the need to improve the efficiency of the functioning of electric power systems, a large number of electricity market participants able to manage their own schedules of electrical loads have led to the gradual integration of demand management technologies into the energy market environment in many countries of the world. A large number of scientific works of this stage are focused on assessing the impact of overloading the electric power system during periods of seasonal growth in demand or daily peaks on the functioning of energy markets and, as a result, on analyzing the possibilities of effective application of mechanisms of demand management for levelling congestion. Among the most significant works in this area are the studies of Hamoud[80], Mendez[81], Capozza[82], Kumar[83].

On the background of the development of information and communication technologies, fifth stage, which have become widely used in the electric power industry since the beginning of 2009, the concept of "Smart Grid" technologies (Smart power supply networks) has been developed. Smart Grid technology allows, through integration with power generation systems, power storage systems, to improve the management of demand for power consumption at various levels of the power system, which leads to an increase in the sustainability and reliability of power supply to consumers. Assessing the risks of using smart technologies and developing scenarios for their implementation, of particular practical importance are the works in the field of integrating the concept of "Smart Grid" and demand management technologies.

A prerequisite for the formation of the modern stage of scientific research is the development of distributed generation technologies, renewable energy sources (RES), and industrial energy storage systems. The effectiveness of the use of DSM technologies and the increase in the availability of renewable energy sources have led to the emergence of a significant number of scientific works devoted to the integration of demand management

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[80] Hamoud, G. 2004. Assessment of transmission congestion cost and locational marginal pricing in a competitive electricity markets / G. Hamoud // IEEE Trans. Power Syst. № 19. 769–775. DOI: 10.1109/TPWRS.2004.825823. [Accessed 10.12.2019]

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[82] Capozza, A. 2005. Load shedding and demand side management enhancements to improve the security of a national electrical system / A. Capozza, C. D'Adamo, G. Mauri, A. Pievatolo // 2005 IEEE Russia Power Tech Date of Conference. 1-7. DOI: 10.1109/PTC.2005.4524568. [Accessed 10.12.2019]

[83] Kumar, A. 2005. Congestion management in competitive power market: A bibliographical survey / A. Kumar, S.C. Srivastava, S.N. Singhb // Electric Power Systems Research. Vol. 76, Issues 1–3. 153–164. https://doi.org/10.1016/j.epsr.2005.05.001 [Accessed 17.12.2019]

models with modern trends in technologies of alternative or small distributed generation, aimed at the comprehensive improvement of DSM technologies.

The most significant studies devoted to the integration of demand management technologies with renewable energy sources are the works of Knudsen[84], Foucault[85], S. Pholboon[86], S. Kwon[87], Yu Wu[88], etc. These authors have developed general models of demand management based on the penetration of renewable energy sources, small generation systems and energy storage systems into the interconnected power systems, systematized the risks and management features of such systems. Among the studies devoted to the integration of wind farms with DSM systems, one can highlight the work carried out under the leadership of Anderson[89] and Na[90]. The studies of the integration of photovoltaic components are described in the works of Khalid[91], Chichek[92], and Lee[93] proposing optimal models for integrating wind and solar power systems into interconnected power systems, and taking into account the mechanisms of demand management. The studies of the integration of the operation of

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[84] Knudsen, J. A. 2016. Dynamic Market Mechanism for the Integration of Renewables and Demand Response / J. Knudsen, J. Hansen, A.M. Annaswamy // IEEE Transactions on Control Systems Technology. Vol. 24, Issue: 3. 940–955. DOI: 10.1109/TCST.2015.2476785. [Accessed 17.12.2019]

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[86] Pholboon, S. 2017. Adaptive power flow control for reducing peak demand and maximizing renewable energy usage / S. Pholboon, M. Sumner, Kounnos // 2017 International Electrical Engineering Congress (iEECON). 1–4. DOI: 10.1109/IEECON.2017.8075737. [Accessed 16.12.2019]

[87] Kwon, S. 2017. Optimal Day-Ahead Power Procurement with Renewable Energy and Demand Response / S. Kwon, L. Ntaimo, N. Gautam // IEEE Transactions on Power Systems. Vol. 32, Issue: 5. 3924–3933. DOI: 10.1109/TPWRS.2016.2643624. [Accessed 14.12.2019]

[88] Wu, Y. 2014. Optimal Energy Scheduling for Residential Smart Grid with Centralized Renewable Energy Source / Y. Wu, V. Lau, D. Tsang, L. Qian, L. Meng // IEEE Systems Journal. Vol. 8, Issue: 2. 562–576. DOI: 10.1109/JSYST.2013.2261001. [Accessed 17.12.2019]

[89] Anderson, C. L. 2014. A Decision Framework for Optimal Pairing of Wind and Demand Response Resources / C.L. Anderson, J.B. Cardell // IEEE Systems Journal. Vol. 8, Issue: 4. 1104–1111. DOI: 10.1109/JSYST.2014.2326898. [Accessed 17.12.2019]

[90] Na, Y. 2014. Coordination and optimization model of wind power grid integrated system considering demand response / Y. Na, C. Shenyu, S. Linlin // 2014 International Conference on Power System Technology. 949–955. DOI: 10.1109/POWERCON.2014.6993919. [Accessed 17.12.2019]

[91] Khalid, M. 2014. Optimal hybrid wind-solar system for matching renewable power generation with demand / M. Khalid, A.V. Savkin, V.G. Agelidis // 11th IEEE International Conference on Control & Automation (ICCA). 1322–1326. DOI: 10.1109/ICCA.2014.6871115. [Accessed 17.12.2019]

[92] Çiçek, N. 2014. Demand response for smart grids with solar power / N. Çiçek, H. Deliç // 2014 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA). 566–571. DOI: 10.1109/ISGT-Asia.2014.6873854. [Accessed 17.12.2019]

[93] Lee, J. I. 2014. Solar energy management internetworking with demand response / J. I. Lee, I. W. Lee // 2014 International Conference on Information and Communication Technology Convergence (ICTC). 749–750. DOI: 10.1109/ICTC.2014.6983277. [Accessed 17.12.2019]

industrial energy storage systems in the process of managing the demand for electricity consumption have been carried out in the works of Mocci[94], Rassaei[95], Lopez[96].

Table 1.2

Authors of academic work and stages of the genesis of the world research in the field of energy demand management

Stage	**Stage name**	**Scientists**
1. 1971 – 1980	Identification of the problem of demand volatility, systematization of knowledge and mechanisms in the field of demand volatility management	Dunlop, Wilson, Jacobs, Spencer, Eldridge, Banghart, Elbel, Rivkin, Vercellotti, Whyte, G. Kaplan, Beaty, Hastings, Stocker, Laaspere, Converse, Laaspere, Morgan, Parker, Tuma, J. Lee, Talukdar, Whitaker, Nelson, Schweizer, Bossert, Preiss, Warnock, Morton, Nissel. Walker, Requin and Lorgeau, Mitchell, Wenders, Grainger, Teed, Crespo, Jefferson, Malko, Mitchell, Manning, Stillhavd, Serfass, Adams, Long, Mohre, Looney, Saylor, Morgan, Cohen, Christensen, Gerber.
2. 1980 – 1994	Start of implementation of electricity demand management programs in the forms of regional Aggregators	Gellings, Chan, Ackerman, Calloway, Brice, Walker, Pokoski, Engle, Yoo, Aggoune, Findlay, Birdwell, Khosid, Granger, Hallman, Delgado. Gellings, Limaye, Garcia, Johansson, Bjork, Karlsson, Beenstock, Billington, Levine, Liu, Bowie, Mills, Vine, Ghani, Hobbs, Rouse, Hoog Coleman, Garrett, Engle, Granger, Hylleberg, Lee, Busch, Geller, Moreira, Ross, Liu, Erichsen, Haase Caramanis, Bohn, Schweppe, Caramanis, Tabors, Bohn, Flairn, Krantz, Kirsch, Sullivan, Davis, Jones, Nirenberg, McInnis, Sparks, Lescoeur, Galland.
3. 1994 – 2004	Development and implementation of electricity demand management programs in the forms of regional Aggregators in various countries of the world	Vine, Campanano, Liu, Sinton, Yang, Levine, Ting Thomas, Parikh, Banarjee, Hancke, Bandala, Blanc, Buen, Etzinger, Hancke, Lane, Hancke, Govender, Lombard, Mathews, Kleingeld, Fouquet, Seppala, Mandal, Sinha, Majumdar, Chattopadhyay, Parikh, Sargunaraj, Gupta, Devi, Banerjee, Beenstock,Goldin, Nabot, Popovic, Gjengedal, Lund, Flolo, Crossley, Hamrin, Vine, Eyre, Crossley, Clark, Gajjar, Tajularas, ParachaDoulai, Hirst, Cavanagh, Miller, Rosenstock, Gaul, Handschin, Hoffmann, Shwehdi, Khan, Slingerland, Bernard, Roland, Raad, Srisuwan, Suesut, Boyle, Luís Sauer, Mercedes, Herrera, Chen-Apuy Chacón, Hwang Teive,Vilvert, Chao, Lee, Chang, Weisbrod, Tribble, Deshpande, Gardner, Mathur, Ashok, Banerjee etc.

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[94] Mocci, S. 2014. Multi-agent control system to coordinate optimal electric vehicles charging and demand response actions in active distribution networks / S. Mocci, N. Natale, F. Pilo, S. Ruggeri // 3rd Renewable Power Generation Conference (RPG 2014). 1–6. DOI: 10.1049/c2014.0841. [Accessed 14.12.2019]

[95] Rassaei, F. 2015. Demand Response for Residential Electric Vehicles with Random Usage Patterns in Smart Grids / F. Rassaei, W-S. Soh, K.-C. Chua // IEEE Transactions on Sustainable Energy. Vol. 6, Issue: 4. 1367–1376. DOI: 10.1109/TSTE.2015.2438037. [Accessed 17.12.2019]

[96] López, K. L. 2018. Demand-Side Management using Deep Learning for Smart Charging of Electric Vehicles / K.L. López, C. Gagné, M-A. Gardner // IEEE Transactions on Smart Grid. Vol. PP, Issue: 99. 1–3. DOI: 10.1109/TSG.2018.2808247. [Accessed 17.12.2019]

Table 1.2 continued

Stage	Stage name	Scientists
4. 2004 – 2009	Integration of Demand Response Models into the Electricity Market System	Toomey, Zhenfang, Shunmin, Yixin, Aguado, Quintana, Madrigal, Rosehart, Miguelej, Rodriguej, Canizares, Chen, Milano, Singh, Ventosa, Ramos, Rivier, Fleten, Pettersen, Zhang, Zhao, Han, Niu, Wang, Barroso, Cavalcanti, Giesbertz, Purchala, Rothleder, Besanger, Melby, Yang, Palombi, Bustamante, Fluckiger, Chown, Hedgecock, Diya, Blumsack, Fernands, Hamoud, Mendez, Capozza, Mauri, Pievatolo, Kumar, Schellenberg, Rosehart, Doudna, Widergren, Lawrence, Mickey, Jones etc.
5. 2009 – 2014	Integration of consumption demand management technologies of electricity with the Smart Grid concept	Gellings, McDaniel, McLaughlin, Vos, J. Lu, Kadar, Wolfs, Balijepalli, Saffre, Gedge, Leach, Cappers, Goldman, Kathanb, Paulus, F. Borggrefe, Lino, Valenzuela, Ferreira, Barroso, Bezerra, Pereira, Fernands, Thakur, Morales, Pinson, Madsen, Davies, Mak, Darby, Mohsenian-Rad, A. Leon-Garcia, Bernard, Emec, Kuschke, Chemnitz, Barton, Huang, Leach, Ogunkunle, Torriti, Dwolatzky, Khan, Xu, Slootweg, Martinez, Meyer, Malik etc.
6. 2014 – to the present	Implementation of distributed energy technologies, renewable energy sources, Electric Vehicles and the Internet of Things	Foucault, Girard, Kariniotakis, Knudsen, Hansen, Kwon, Gautam, PholboonKounnos, Wu, Reddy, Kumar, Mallick, Anderson, Cardell, Y. Na, C. Shenyu, S. Linlin, Khalid, Agelidis, Lindberg, Zahedian, Solgi, Çiçek, Tanaka, López, Gagné, Gardner, Sark, Worrell, Narimani, Mocci, Natale, Pilo, Ruggeri, Rassaei, Aburukba; Landolsi, M. Rashid, Hassan, Nunna, W. Zhao, D. Zhao, M.G. Yao etc.

Source: developed by the author based on the literature collected by the author.

The continuing development of information technology leads to the emergence of new technological trends in the electric power industry, such as microgrid, Internet of Things (IoT), Internet of Energy (IoE). The introduction of new technologies is being actively researched for integration with modern DR concepts. Within the framework of these areas, the work of researchers Aburukba[97], Nunna[98], Shahryari[99].

The analysis and systematization of the stages of the genesis of scientific research in the field of demand management for electricity consumption allow us to conclude that the development of scientific research is influenced by both external factors in relation to the

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[97] Aburukba, R.O. 2016. IoT based energy management for residential area / R.O. Aburukba, A.R. Al-Ali, T. Landolsi, M. Rashid, R. Hassan // 2016 IEEE International Conference on Consumer Electronics-Taiwan (ICCE-TW). 2. DOI: 10.1109/ICCE-TW.2016.7521035. [Accessed 17.12.2019]

[98] Nunna, K. 2016. A multi-agent system for energy management in smart microgrids with distributed energy storage and demand response / K. Nunna, D. Srinivasan // 2016 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES). 1–5. DOI: 10.1109/PEDES.2016.7914490. [Accessed 17.12.2019]

[99] Shahryari, K. 2017. Demand Side Management Using the Internet of Energy Based on Fog and Cloud Computing / K. Shahryari, A. Anvari-Moghaddam // 2017 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData). 931–936. DOI: 10.1109/iThings-GreenCom-CPSCom-SmartData.2017.143. [Accessed 17.12.2019]

electric power industry, such as economic crises, the spread of information technologies, and internal factors, such as the development of energy markets, the development of technologies for distributed and renewable energy sources, the emergence of new technological trends.

1.2 Electricity Demand Response optimizations models for implementation of a regional aggregator

Let us peruse findings from the investigation so far. Firstly, according to Stimson at al[100]: "Regional Economic Development is the utilization of economic processes and available resources that result in the sustainable development of the region and the desired economic development results for the region and that meet the values and expectations of entrepreneurs, residents and immigrants." Secondly, the main principle of electricity market clearing is maximization of the social welfare. The social welfare is the sum of the consumer surplus, the supplier surplus and the congestion rent. Moreover, we are trying to increase electricity demand elasticity with hope to engage in the process electricity consumers (who could be also prosumers if they willing participate in electricity market).

When a consumer decides on its own to use less electricity when it is more expensive (e.g. in the peak hours) and use it more when it is cheaper (e.g. at night) it becomes demand response, i.e., final consumers (demand-side) responds to the market incentives. There are two pre-conditions:

- Consumer must have a dynamic electricity price agreement with its' electricity supplier;
- Consumer must have a smart electricity meter installed.

A dynamic electricity price agreement with the electricity supplier means that the consumer pays for the electricity the real-time power exchange market's tariff. There will be a risk of high electricity price fluctuations, but it can also become very advantageous for the consumer in a longer low-price period.

Thus, in response to adequate price signals, demand load modification could have positive economic impact on society as a whole by stimulating efficiency of markets. However, according to[101] DR potential in the EU electricity markets is believed to be high but currently underutilized, especially for residential consumers, on account of current institutional arrangements that cater to large generators and industrial customers.

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[100] Stimson R., Stough R., Roberts B. H. 2002. Regional Economic Development: Analysis, and Planning Strategy, Springer, Berlin.

[101] European Commission Delivering the Internal Electricity Market and Making the Most of Public Intervention Communication from the Commission (2013).

In the light of the foregoing, in this study the author proposes to investigate DR Aggregator objectives and economic benefits to define criteria for the optimization problem.

For the study interest, the author of the Thesis offers citations of the frequently mentioned definitions of DR Aggregators in the academic literature and policy documents. (See Table 1.3). According to [102] the potential benefits of DR are associated with economic, environmental, and reliability ones.

Table 1.3

DR benefits in most frequently cited definitions of DRA

DR benefits	Definitions of DR Aggregator
Economic Environmental Reliability	"DR includes all intentional electricity consumption pattern modifications by end-use customers that are intended to alter the timing, level of instantaneous demand, or total electricity consumption."[103] "Demand Response refers to a wide range of actions which can be taken at the customer side of the electricity meter in response to particular conditions within the electricity system (such as peak period network congestion or high prices)."[104] "The very broad definition of demand response includes both modification of electricity consumption by consumers in response to price and the implementation of more energy efficient technologies."[105] "Changes in electric usage by end-use consumers from their normal load patterns in response to changes in electricity prices and / or incentive payments designed to adjust electricity usage, or in response to the acceptance of the consumer's bid, including through aggregation."[106]

Source: created by the author

That way, economic benefits compromise with reduction of the general cost of energy supply while preserving adequate reserve margins and mitigating price volatility by means of short-term responses to electricity market conditions. Environmental-driven DR would serve environmental and social purposes by decreasing energy usage, increasing energy efficiency, defining commitment to environmentally friendly generation[107], and reducing greenhouse gas emissions. Lastly, network-driven DR aims to maintain system reliability by decreasing

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[102] Aghaei, J., Alizadeh, M.-I. 2013. Demand response in smart electricity grids equipped with renewable energy sources: a review Renew. Sustain. Energy Rev., 18. 64–72 [Accessed 19.0120]

[103] J. Torriti, M.G. Hassan, M. Leach. 2010. Demand response experience in Europe: policies, programmes and implementation Energy, 35. 1575–1583, 10.1016/j.energy.2009.05.021 [Accessed 19.0120]

[104] Albadi, M.H., El-Saadany, E.F. 2008. A summary of demand response in electricity markets Electr. Power Syst. Res., 78. 1989–1996, 10.1016/j.epsr.2008.04.002

[105] Greening, L. A. 2010. Demand response resources: who is responsible for implementation in a deregulated market? Energy, 35. 1518–1525, 10.1016/j.energy.2009.12.013 [Accessed 17.0120]

[106] ACER Framework Guidelines on Electricity Balancing. 2012. Ljubljana. Available from: http://www.acer.europa.eu/official_documents/public_consultations/closed%20public%20consultations/dfgeb2012e004_pc_docs/initial%20impact%20assessment.pdf Accessed [12.09.2020]

[107] Batlle C., Rodilla P. 2009. Electricity demand response tools: current status and outstanding issues Eur. Rev. Energy Mark., 3. 1–27.

demand in a short period of time and reducing the need to enhance generation or transmission capacity.

As mentioned in the Thesis Chapter 1.1, DR activisation in the electricity system could be either interruptible or price-based. Electricity pricing is an important method by which end-user demand response can be incentivized while maintaining voluntary choice. The general composition of the cost allocation elements in the liberalized electricity market model (mainly prevailing in Europe) is presented in Figure 1.3.

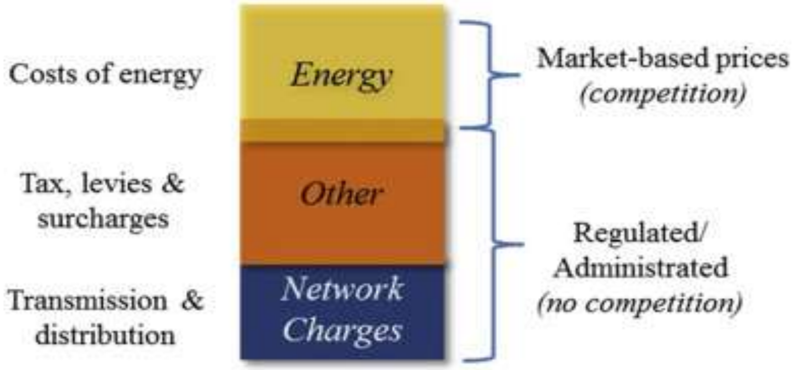

Figure 1.3 **Usual breakdown of electricity retail rates in a liberalized electricity market**.[108]

Transition, enabled by smart-grid technologies, increasing levels of demand are now served by stochastic supply from renewable resources, requires that electricity consumers receive real-time reflective information regarding the electricity prices through dynamic pricing. In Latvia, not all electricity consumers are equipped with smart electricity meters that were mentioned in the introduction part as a prerequisite for receiving demand response services. Currently about 60 % of all electricity meters in Latvia are smart meters, but it is planned that all electricity meters will be updated to smart meters by 2022.

It can be argued that the entry of aggregators into the smart-grid environment where demand participation is fostered, end-user tariffs can incorporate customer categorization, time and location, and Aggregator can set-up in a smart-grid environment where demand participation is fostered, end-user tariffs can incorporate customer categorization, time and location. (See Figure 1.4)

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[108] Eurelectric Network Tariff Structure for a Smart Energy System. Brussels. 2013. Retrieved from www.eurelectric.org Accessed [12.09.2020]

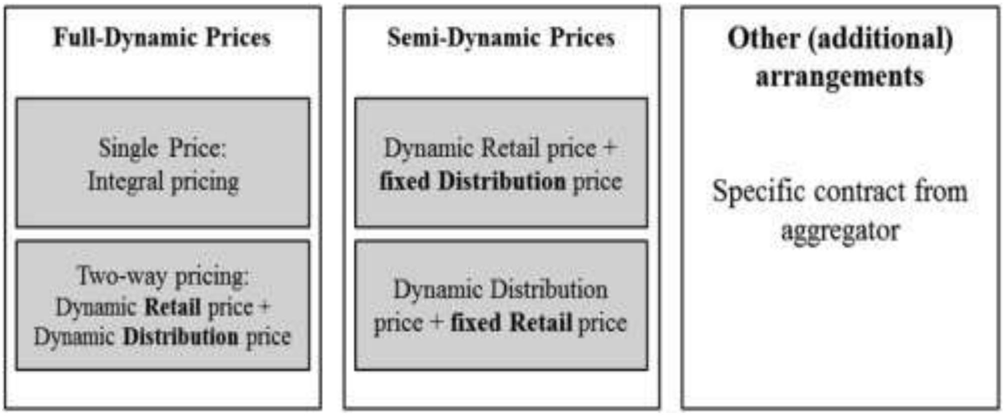

Figure 1.4 **Different billing methods to incentivize demand response.**[109]

Optimization of DR mechanisms obtains the best possible variables to maximize or minimize an objective function value, provided that the variables are bounded by a set of constraints[110].

Analysing the literature on the objects of DR (See Chapter 1.1.1 Genesis of DR) results were obtained as following:

Ob1 Cost minimization for a (single) participant (savings in electricity bills) or even market-wide (e.g., through more efficient use of the infrastructure).

Ob2 Minimization of peak loads in the consumption profile, to reduce the need of high spinning reserves, etc.

Ob3 Load profile flattening by shifting demand, thereby reducing the cost of producing electrical energy.

Ob4 Ensuring reliability to reduce the risk of outages and ensure the ability to react to contingencies by holding a spinning reserve.

Ob5 Maximization of market performance by allowing consumers to affect the market, thereby reducing price volatility in the spot market.

Ob6 Maximization of users' utility (often also called welfare), to maximize the users' comfort and preferences.

Ob7 Efficiency of infrastructure usage to save external kWh.

Optimization problems can be categorized according to several criteria. Depending on nature (degree in the polynomial form of the function) of the objective functions and constraints involved, linear and nonlinear optimization exists. If at least one of the objective functions and / or constraints is nonlinear, the problem is said to be nonlinear optimization. A mixed

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[109] Eid, Ch., Reneses, J., Frías, P., Hakvoort, R. 2013. Challenges for Electricity Distribution Tariff Design in the Smart Grid era: A Conceptual Approach [Accessed 29.11.2020]

[110] Vardakas J. S., Zorba N., Verikoukis C. V. 2014. A Survey on Demand Response Programs in Smart Grids: Pricing Methods and Optimization Algorithms, *IEEE Commun. Surv. Tutorials*, vol. 17, no. c. 1–1, [Accessed 29.11.2020]

integer programming problem denotes whether some of the variables are integers. Additionally, based on the nature of the variables (deterministic or the stochastic) involved, optimization problems can be classified into deterministic and stochastic programming problems; the latter case describes optimization models that deal with RES, due to the stochastic nature of these sources.[111]

As have been mentioned before, all EU countries both buy and sell electricity on the NordPool exchange. Many of them, including Latvia, import more electricity than they sell. Therefore, the optimization of the balance of supply and demand is an important task, for the solution of which a two-stage optimization methodology is proposed. To solve the problem of implementation of DR Aggregator of electricity, it is necessary to develop appropriate mathematical models and methods for their application, which are applied on the basis of forecast information on the amount of electricity shortage and its cost upon purchase.

For the DR Aggregator problem could defined as following: DRA should react to events of overcapacity energy consumption providing a real time list of appliances to be switched off to restore a desirable energy consumption. In particular, in case the sum of appliances electrical absorption exceeds a predetermined value, the Demand Response Aggregator should calculate the amount of energy to cut off and identify the appliances to be switched off to minimize a function of discomfort for users.

Table 1.4

The Proposed Optimization Classification Compared with Methods Reviewed in Literature (made by the author)

Optimisation Objective	Optimisation Method	Active Consumers (AC) Groups	Demand Response Pricing
Maximising the energy consumption based on the choice of AC groups	Combinatorial optimisation (linear integer programming)	Choice of AC groups	Real time pricing (a day-ahead or an hour-ahead)

Source: created by the author.

A household aggregator will need a large portfolio of households to influence and run a profitable business. As an entrepreneur working in an aggregation project in Estonia explained in an interview, household aggregators focus on household appliances such as electric heaters, boilers, heat pumps, air conditioners and thermostats. They can be easily monitored from a distance and without disrupting the daily lives of consumers, who will not feel discomfort due

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[111] Ribó-Pérez, D., Larrosa-López, L., Pecondón-Tricas, D., Alcázar-Ortega, M. 2021. A Critical Review of Demand Response Products as Resource for Ancillary Services: International Experience and Policy Recommendations. Energies, 14. 846. https:// doi.org/10.3390/en14040846[Accessed 28.07.2019].

to restrictions on the use of electricity. However, as the aforementioned entrepreneur explained, the aggregator must have at least 10.000 consumers who are saving 5 kWh per day in order to make it a profitable business. For example, a general overview of online offers for electrical appliances shows that the average AHU / heat pump consumes about 5–15 kWh per hour, so the reduction in electricity consumption by 5 kWh per day is not really that much when you consider this fraction of the amount of electricity. will still be consumed, but at other times of the day, when electricity prices will be lower.

A crucial factor that must not be forgotten when developing mathematical optimization models, however, is their ease of implementation and peculiarities caused by application to a particular system. In other words, to have a practical purpose the mathematical model has to be implemented in an actual software tool that can be deployed on an Aggregator operator's workstation and would allow the software to utilize it.

Thus, at the first stage, based on predicted data on the shortage of electricity for the next day, it is proposed to solve the problem of reducing its consumption. At the second stage, the choice of active consumers to be switched off for the current hour is optimized if the amount of electricity is not sufficient, even considering a decrease in its consumption. The developed methodology (See Chapter 3) should be based on the corresponding mathematical models at each of their stages, for which the corresponding optimization problems should be formulated at each stage.

Conclusions

1. The author has analysed the definitions and classifications of the electricity consumption response (DR) The author has developed a chronology of the development of electricity Demand Response – the genesis of scientific research. The analysis and systematisation of its stages allows to conclude that the development of scientific research is influenced by both external factors related to electricity, such as economic crises, the spread of information technologies, and internal factors, such as the development of energy markets, the development of distributed and renewable energy technologies, the emergence of new technological trends.
2. Due to the nature of renewable, it is not possible to control or request power when it is needed. The main objectives of Demand Response techniques are reduction of peak load and the ability to control consumption according to generation. Usually, end-users have very little practical knowledge about their flexibility and are

unaware of their usage patterns and behaviour. Hence, participants in DR programs show a lower response than the expected levels.

3. The analysis of various tools for managing the demand for electricity consumption, as well as functioning demand management programs in the countries of the world, allows us to state a significant differentiation and specificity of such tools and programs in the country context. A retrospective analysis of the scientific development of electricity consumption response by developing a classification of electricity Demand Response programmes in different countries. It is important to note that the Demand Response programs shown in Table 1.1 are not interchangeable and all of these mechanisms can be used in a complex.
4. The author of the Thesis proposed combinatorial optimization for implementation of the concept of regional Demand Response Aggregator, that will allow to solve the problem of reducing electricity consumption and, at the second stage, the choice of active consumers to be switched off for the current hour is optimized if the amount of electricity is not enough, even considering a decrease in its consumption.

2 Economic environment indicators of the Demand Response in the electricity market

This part of the Thesis, in order to achieve the goal, set in the work, presents the review and analysis of economic environment for DR Aggregator implementation, discusses the impact of renewable energy sources to the system price of electricity. First, the author reveals the peculiarities of electricity price on Nord Pool exchange, then continues on the subject of economic and financial indicators for activation DR Aggregator in the electricity system

2.1 Electricity market liberalization process

Electricity, as a commodity, has special characteristics that make it different from others. First, it is currently expensive to store electricity in big quantities; therefore, generation and load need to be matched continuously. Second, electricity systems need physical infrastructure to connect and match supply and demand. The physical infrastructure is complex and has different components such as the grid, transformers, protection devices, etc. Third, electricity systems are interconnected across national borders and electricity flows follow physical rules, such as Kirchhoff's laws, instead of pathways defined by contracts. These characteristics make electricity system operation a difficult task.[112] Electricity systems, in Europe and around the world, used to be considered natural monopolies. In most countries, a single national company was in charge of the system operation, owned all the physical assets (generation units and grid components), and delivered electricity to final consumers. However, since the 1990's, the electricity systems in the EU have been transformed from national monopolies into a liberalized environment, where power generation and the supply of energy services are taking place in competitive markets, and the reforms are still ongoing. In the current liberalized context, the economic dimension of electricity systems has been organized into different markets, catering for long-term and short-term arrangements over a range of time constants. The design and organization of these markets define the responsibilities of the different actors and delimit their actions. One of the main actors is the System Operator (SO)[113], who is in charge of the system balance, security and reliability. The SOs usually buy system services from market parties (from both supply and demand sides) and take actions in real time to achieve their objectives. On the other hand, market parties, such as generators, suppliers and

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[112] Keay M. 2016. Electricity markets are broken – can they be fixed? The Oxford Institute for Energy Studies EL 27. 1–39. doi:10.1006/ clim.2000.4836.

[113] JSC Augstsprieguma tīkls. Latvian electricity market overview. [Online]. Available at: http:// www.ast.lv/ en/electricity-market-review?year=2017&month=10 [Accessed 16.02.2020]

traders, buy and sell electricity in the different markets and are constrained by market rules and network codes.

Deregulation of electricity market so that there are several institutions running various components of the grid has the potential to improve efficiency, reliability and stability of the grid. Moreover, customers can have their electricity costs reduced and additionally can get value-added services because of competition among utilities. Typically, deregulation of electricity market means having several players in generation and retail supply while keeping transmission and distribution components legal monopolies.[114] This provides an opportunity for customers to choose their preferred cost / service quality package from multiple competing utilities.

More effective use of Europe's energy potential requires the involvement of all energy market players[115]. The core of any business model is a consumer. A consumer is the point of reference that defines the vector of business development. Today, the energy industry is undergoing a transformation where the consumer is no longer just a point; it turns into a vector itself.

Decentralization of the power system through the involvement of active consumers, citizens and local authorities in the operation of the system is currently widely used in Europe. Active consumers are defined as electricity consumers that use, store or sell their own electricity or participate in demand change and energy efficiency schemes[116].

The Latvian electricity market has been liberalized since 2015, and households as well as legal users can freely choose their trader by agreeing on the electricity price. Since 2013, electricity trading has also been carried out within the Nord Pool exchange. Currently, 38 companies operate on the Latvian electricity market. The Latvian electricity market, like the entire Baltic energy market, is currently linked to the common European energy market by two cables connecting the power systems of Estonia and Finland: Estlink I with a transmission capacity of 350 MW and Estlink II with a transmission capacity of 650 MW. Lithuania-Poland is connected by a LitPol Link interconnection with a transmission capacity of 500 MW. It is

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[114] Nooriya, A.M., Albadi, M.H. 2020. Demand response in electricity generation planning, The Electricity Journal, Volume 33, Issue 7, 106799, ISSN 1040-6190, https://doi.org/10.1016/j.tej.2020.106799. (https://www.sciencedirect.com/science/article/pii/S1040619020300919) [Accessed 14.10.2021]

[115] European Committee of the Regions, Commission for the Environment, Climate Changes and Energy. Models of Local Energy Ownership and the Role of Local Energy Communities in Energy Transition in Europe. 2018. [Online]. Available at: https:// oeuropa.eu/en/publication-detail/-/publication/667d5014-c2ce-11e8-9424-01aa75ed71a1/language-en/format-PDF/source-77208198 [Accessed 16.02.2020]

[116] European Committee of the Regions, Commission for the Environment, Climate Changes and Energy. Models of Local Energy Ownership and the Role of Local Energy Communities in Energy Transition in Europe. 2018. [Online]. Available at: https:// oeuropa.eu/en/publication-detail/-/publication/667d5014-c2ce-11e8-9424-01aa75ed71a1/language-en/format-PDF/source-77208198 [Accessed 16.02.2020]

also complemented by the Lithuanian-Swedish interconnection NordBalt with a transmission capacity of 700 MW[117]. One of the most important news in the electricity market is the planned integration and synchronisation of electricity networks of Baltic States with the European network (hereinafter referred to as the synchronisation project), work on which started in 2007, when Prime Ministers of the Baltic countries proposed the idea to investigate into such an opportunity. This project is at the top of the EU energy policy agenda and is one of priority projects not only at the level of Baltic countries, but also at the EU level, because by construction of additional electricity interconnections it improves functioning of the EU's internal energy market and the achievement of goals of the Energy Union. The synchronisation project is part of the total EU integration project, the implementation of which is intended until 2025.

Evidently, the more liberalized the market, the more it responds to fluctuations in demand and supply. In an effort to maximize the liberalization of the European energy market, European market decision makers intended to use it as a tool that would provide an ever-increasing, growing and diversified range of offers, which would put downward pressure on prices.

According to the Regulation of the Cabinet of Ministers developed on 02/04/2020, in order to increase the stability and security of the energy system, it is necessary to develop a legal basis for the operation of aggregators until 2022, to define the rights and obligations of the aggregator, payments for its services and relations between the aggregator and other participants in the system and the market. This will increase the balancing capacity and flexibility of the system.

High final electricity prices impose a significant cost burden on households and generating companies, thus also affecting the country's competitiveness. Electricity prices are determined by various factors[118], such as fuel structure, cross-border interconnections, markets interconnection, renewable energy, concentration of market suppliers, weather conditions, etc.[119]

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[117] Legal acts of the Republic of Latvia. Electricity Market Law. [Online]. Available at: https:// likumi.lv/ ta/en/en/id/108834-electricity-market-law [Accessed 19.01.2020]

[118] Sauhatas, A., Baltputnis, K. 2017. *Price of Electricity and Its Influencing Factors* Riga Technical University. Academic Search Complete. [Online]. Available at: https://www.em.gov.lv/files/attachments/ Elektroenergijas_cenu_petijuma_nosleguma_zinojums_2017-05-31.pdf.. ID 25645, [Accessed 14.11.2020]

[119] Cappers P., Mills, A., Goldman, C., Eto, J., Wiser, R. 2011. Mass Market Demand Response and Variable Integration Issues: A Scoping Study; Lawrence Berkley National Library: Berkley, CA, USA, [Accessed 17.12.2020]

The current electricity market setup has been able, to some extent, to deliver competitiveness and low prices to consumers for many years. However, the growing awareness of climate change and the development of national and international agreements aiming to reduce greenhouse gas (GHG) emissions are transforming the sector significantly[120], and not always for a good.

On 30 November 2016, the European Commission issued a report entitled 'Energy prices and costs in Europe', which stated that, although wholesale energy prices in the European Union reached their lowest levels in 12 years in 2016, household prices have risen by an average of 2–3 % per year, but electricity prices for industrial consumers increased by about 2 %[121]. Concluded that Member States need to better assess the need for such mechanisms, while ensuring security of energy supply while minimizing competition distortions and keeping electricity prices paid by consumers low[122].

In the beginning of 2020, following the requirements of the above-mentioned Directive 2012/27/EU, the Cabinet of Ministers of Latvia approved the first rules on the functioning of aggregators in Latvia[123]. The relationship of the aggregator with other participants in the electricity system and the market in Latvia is determined by this Decree of the Cabinet of Ministers. The regulation defines the rights and obligations of aggregators, payments for the services provided by aggregators[124], as well as define relations between the aggregators and other electricity market's participants. The rules increase the ability of electricity consumers or third parties of their choice to handle electricity consumption information in order to provide a mechanism by which consumption can be adjusted quickly.

According to[125] European energy markets have been liberalized since the second half of the 1990s. The focus of the first three energy packages (1996–2009) was on founding the internal energy market: the introduction of competition for generation and supply, ensuring non-discriminatory access to distribution and transmission networks, improving cross-border trade, and establishing a governance structure (e.g., national and international regulators). The position of small energy consumers—households and small and medium-sized enterprises – has

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[120] United Nations, Paris Agreement, Technical Report, 2015 [Accessed 17.12.2020]

[121] Energy BrainBlog. Trends in the development of electricity prices – EU Energy Outlook 2050. 15 June, 2017. [Online]. Available at: https://blog.energybrainpool.com/ en/trends-in-the-development-of-electricity-prices-eu-energy-outlook-2050/ [Accessed 30.11.2019].

[122] European Commission. 2030 Energy Strategy. [Online]. Available at: https://ec.europa. eu/energy/ en/topics/energy-strategy-and-energy-union/2030-energy-strategy [Accessed 24.10.2019]

[123] Cabinet of Ministers of Latvia, Rules on aggregation, 2020 [Online]. Available at: https://likumi.lv/ ta/id/313461-agregatoru-noteikumi [Accessed 01.09.2020]

[124] Lauka, D. 2018. Sustainability analysis of renewable energy sources. Riga: RTU Press.

[125] Willems, B., Zhou, J. 2020. The Clean Energy Package and Demand Response: Setting Correct Incentives. *Energies*. 13(21). 5672. https://doi.org/10.3390/en13215672 [Google Scholar] [CrossRef], [Accessed 28.07.2020].

only gradually received attention.[126] Where earlier regulations focused on consumers as rather passive agents requiring protection, newer iterations view consumers more as active market participants.[127]

Definition of prosumers

Prosumers are individuals, groups of people, households, or farms that can function in an organized way – for example, through associations, foundations, or cooperatives – that are both producers and consumers of energy, produced in small installations in courtyards or in residential or commercial buildings (for example, miniature wind turbines, photovoltaic panels, solar panels, and heat pumps)[128]. The EU has no specific legislation on prosumers, self-production, or self-consumption, and there is no general definition of prosumers[129]. However, the Energy Efficiency Directive, the Renewable Energy Directive, and the State Aid Guidelines contain provisions for small electricity producers. The EU Parliament called for a common definition of prosumers in the EU and for new energy legislation, with measures to stimulate investment in its own production capacity[130].

European Commission energy strategies

In November 2018[131], The European Commission published a strategic long-term vision for a prosperous, modern, competitive and neutral economy for 2050. The strategy reflects on how Europe can move forward towards climate neutrality by developing new technological solutions and coordinating important areas such as industry, finance and research. It will be

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[126] Directive 96/92/EC of the European Parliament and of the Council of 19 December 1996 concerning common rules for the internal market in electricity, http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31996L0092:EN:HTML. Directive 2003/54/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in electricity and repealing Directive 96/92/EC, http://eur-lex.europa.eu/resource.html?uri=cellar:caeb5f68-61fd-4ea8-b3b5-00e692b1013c.0004.02/DOC_1&format=PDF. Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC, http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:211:0055:0093:EN:PDF [Accessed 22.05.2021].

[127] Willems, B, Zhou, J. 2020. The Clean Energy Package and Demand Response: Setting Correct Incentives. *Energies*. 13(21). 5672. https://doi.org/10.3390/en13215672 [Google Scholar] [CrossRef], [Accessed 22.05.2021].

[128] Pietkiewicz, J. 2016. Prosumer Energy and Prosumer Power Cooperatives: Opportunities and Challenges in the EU Countries (Own-Initiative Opinion); European Economic and Social Committee: Bruxelles, Belgium. 44–52.

[129] Šajn, N. 2016. Electricity Prosumers. Eur. Parlam. Res. Serv. 518–593, 1–10.

[130] Lebedeva, K., Krumins, A., Tamane, A., Dzelzitis, E. 2021. Analysis of Latvian Households' Potential Participation in the Energy Market as Prosumers. Clean Technol., 3. 437–449. https://doi.org/10.3390/cleantechnol3020025 [Accessed 22.05.2021].

[131] European Committee of the Regions, Commission for the Environment, Climate Changes and Energy. Models of Local Energy Ownership and the Role of Local Energy Communities in Energy Transition in Europe. 2018. [Online]. Available at: https:// oeuropa.eu/en/publication-detail/-/publication/667d5014-c2ce-11e8-9424-01aa75ed71a1/language-en/format-PDF/source-77208198 [cit. 16.02.2020]

based on the new energy policy system created in accordance with the „Clean Energy for All Europeans" package which gives the European consumers rights to become active participants in the energy transition stage and sets two new goals for the EU for 2030[132]: at least a 32 % renewable energy target and at least a 32,5 % energy efficiency target – with a possible upwards re-calculation. For the electricity market, it sets a 15 % interconnection target by 2030. Miguel Arias Cañete, the EU Commissioner for Climate Action and Energy, states that the EU is on the right track to achieve the RES target, indicating that Europe is the world's first major economy that is planning on becoming climate-neutral by 2050 and reaching an 80 % RES target. These statements will promote the competitiveness, overall growth and employment of the European industry, decrease electricity costs, help prevent energy loss and improve quality[133].

EU 2030 Energy Strategy targets:

- decrease the greenhouse effect gas emission level by 40 % in comparison to 1990;
- at least 27 % of renewable energy consumption;
- improve energy efficiency at the EU level by at least 27 % (in comparison to the prognosis) which must be reviewed until 2020 (namely, the EU level is 30 %);
- support the improvement of the internal energy market by reaching the electricity interconnection target – 10 % by 2020, in order to reach 15 % by 2030[134].

Energy strategies of the Republic of Latvia

In the Republic of Latvia, the Parliament has issued a development planning document of the highest importance – "Sustainable Development Strategy of Latvia until 2030"[135] – that defines the renewable and safe energy target for the development of the country's energy independence by increasing the energy resource self-sufficiency and integrating in the EU energy network. The strategy is comprised of certain energy development measures, projects and national targets for determining the energy and energy resource self-sufficiency. The main criteria for achieving energy sufficiency and availability is a balanced, effective, economically, socially and ecologically based further development of the industry. To meet the set objectives,

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[132] European Commission. 2030 Energy Strategy. [Online]. Available at: https://ec.europa. eu/energy/ en/topics/energy-strategy-and-energy-union/2030-energy-strategy [Accessed 24.10.2019]

[133] European Commission. 2030 Energy Strategy. [Online]. Available at: https://ec.europa. eu/energy/en/topics/energy-strategy-and-energy-union/2030-energy-strategy [Accessed 24.10.2019]

[134] European Commission. Europe leads the global clean energy transition; latest Eurostat data confirms. Published 12.02.2019. [Online]. Available at: https://ec.europa. eu/info/news/europe-leads-global-clean-energy-transition-latest-eurostat-dataconfirms-2019-feb-12_en [Accessed 27.07.2021]

[135] European Commission: Energy. Latvian Ministry of Economics: Latvia's National Energy and Climate Plan 2021–2030. Available online: https://ec.europa.eu/energy/sites/ener/files/documents/ ec_courtesy_translation_lv_necpdf [Accessed 27.07.2021]

an industry-specific target and action document that covers the essential dimensions of the energy industry – “2030 Energy Strategy” – was created. In order to determine the national priorities for 2030, 7 tightly interrelated directions are put forward:

- decrease electricity and natural gas import from existing third world country suppliers by 50 %;
- achieve the reduction of building heating consumption to 100 kWh / m^2;
- achieve a 50 % renewable energy resource proportion in the final energy consumption as well as increase the renewable energy consumption in transportation;
- guarantee alternative solutions for the supply of natural gas and legal circumstances for opening the natural gas market in Latvia in 2015;
- create electricity and natural gas markets;
- increase the cross-border electricity interconnection capacities in order to reduce the price differences in different energy exchange auction areas;
- offer support for creating an attractive environment for investments and developing the national economy by promoting the transition to energy efficient technologies and reducing energy costs for its users[136].

Some of these objectives have already been obtained some[137] of them partially, but only a common and effective implementation of these performance indicators can guarantee a sustainable development of the energy industry.

Renewable energy resources will mostly dominate when forecasting Europe’s offer. It is expected that by 2050 wind energy will amount to approximately 30 % of the total production capacity. Regarding fossil power, it is planned to build mostly natural gas power plants in Europe. By 2050, nuclear energy and coal power station capacity will decrease to 10 % of the total installed capacity. Overall, the fossil production capacity will be reduced from 50 % to 30 %[138].

The use of energy is the key to humanity. It helps to develop and adapt to the changing environment. Today's society consumes enormous amounts of energy, so the energy sector is very important worldwide. Energy supports all aspects of modern life, contributing to economic growth and prosperity, thus has a direct link to people's living standards.

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[136] European Commission. List of NACE codes. [Online]. Available at: https://ec.europa.eu/competition/mergers/cases/index/nace_all.html [Accessed 28.07.2020]

[137] Legal acts of the Republic of Latvia. Electricity Market Law. [Online]. Available at: https://likumi.lv/ta/en/en/id/108834-electricity-market-law [Accessed 19.01.2020]

[138] European Commission. Europe leads the global clean energy transition; latest Eurostat data confirms. 12.02.2019. [Online]. Available at: https://ec.europa. eu/info/news/europe-leads-global-clean-energy-transition-latest-eurostat-dataconfirms-2019-feb-12_en [Accessed 19.01.2020]

Based on the statistical classification of economic activities in the European Community, NACE Rev. 2, the energy industry is classified as:

- Desection “Electricity, gas, steam and air conditioning supply”
- 35. “Electricity, gas, steam and air conditioning supply”
- 35. 1 “Electric power generation, transmission and distribution”
- 35. 1.1 “Production of electricity”.

This class includes: – the production of electricity from cogeneration units, nuclear power plants, hydroelectric power stations, gas turbines or diesel generators and from renewable energy sources[139]. According to the Central Statistical Bureau last data, there were 347 economically active commercial companies (market sector) in Latvia at NACE D 35.11 in 2017[140]. Latvian enterprise database Lursoft, shows that in March 2019, 489 companies with this NACE code registered in Latvia.

2.2 Regional and economic framework of the electricity sector in the Nord Pool

Electricity is a complex commodity to trade. Thus, electricity markets differ substantially from other commodity markets. This is due to the physical characteristics of electricity:

- *Time*: large volumes of electricity cannot be stored economically (yet). Therefore, electricity has a different value over time.
- *Location*: electricity flows cannot be controlled easily and efficiently, and transmission components must be operated under safe flow limits. If not, there is a risk of cascading failures and blackouts. Therefore, electricity has a different value over space.
- *Flexibility*: demand and generation must match each other at all times; otherwise, there is a risk of blackout. However, demand and the availability of renewable energy resources can vary sharply over time, while some power stations can only change output slowly and can take many hours to start up. In addition, power stations can fail suddenly. Therefore, the ability to change the generation / consumption of electricity at short notice has a value.[141]

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[139] European Commission. List of NACE codes. [Online]. Available at: https://ec.europa.eu/competition/mergers/cases/index/nace_all.html [Accessed 28.07.2020]

[140] Central Statistical Bureau of Latvia. [Online]. Available at: www.csb.gov.lv/en [Accessed 07.08.2020]

[141] Meeus, L., Reif, V. 2020. Why did we start with electricity markets in Europe?.In *The Evolution of Electricity Markets in Europe*, Cheltenham, UK: Edward Elgar Publishing. Available From: Elgar Online: The online content platform for Edward Elgar Publishing<> [Accessed 14.02.2020]

These three unique physical characteristics explain why there is not just one electricity market. Electricity is not only energy in MWh; transmission capacity and flexibility are scarce resources and should be priced accordingly. Therefore, electricity (energy, transmission capacity, flexibility) is exchanged in several markets until the actual delivery in real-time.

Figure 2.1 below shows a schematic overview of the electricity markets that currently exist in the EU. The authors[142] group the markets in four clusters and address these clusters one by one in the following subsections. It is also stated per cluster, which European regulations, in the form of network codes and guidelines,[143] govern these markets.

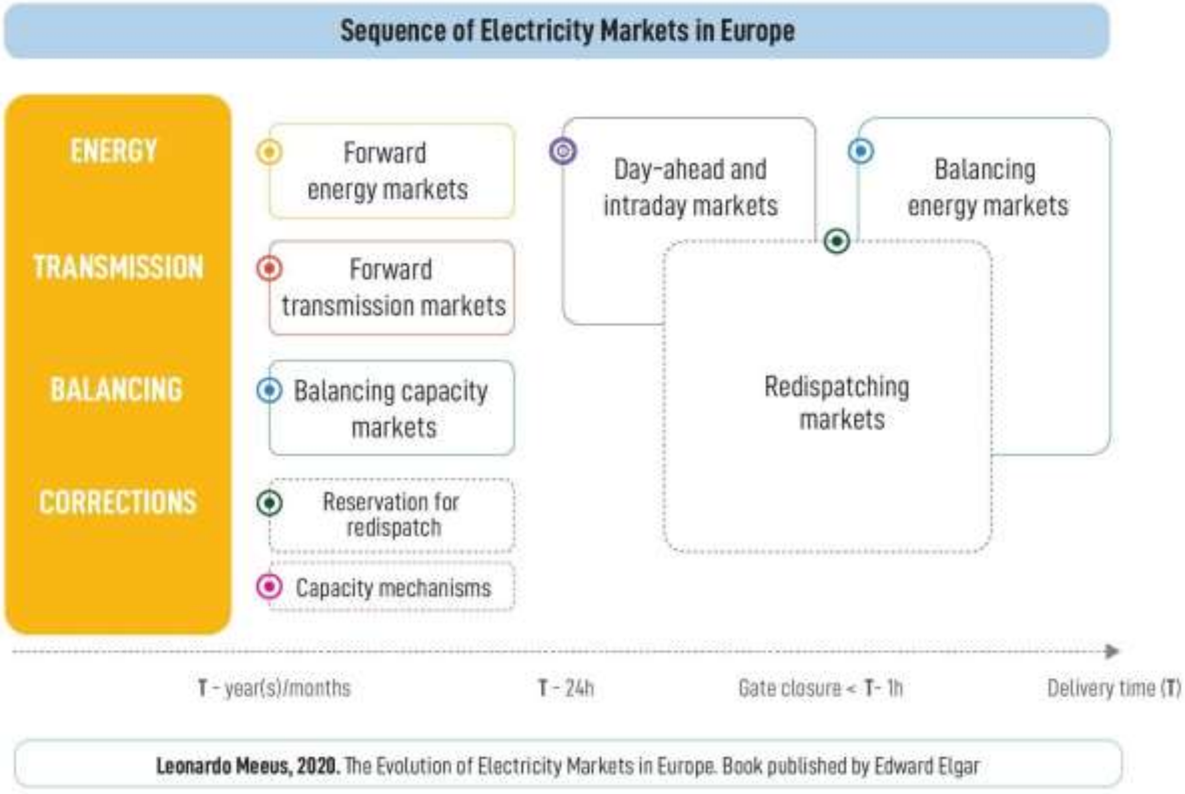

Figure 2.1 **Schematic overview of the typical sequence of existing electricity markets in EU**[144]

Figure 2.1 represents also a long-time and short-time electricity markets

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[142] Meeus, L., Reif, V. 2020. Why did we start with electricity markets in Europe? In the Evolution of Electricity Markets in Europe, Cheltenham, UK: Edward Elgar Publishing. Available From: Elgar Online: The online content platform for Edward Elgar Publishing<https://doi.org/10.4337/9781789905472.00013> [Accessed 14.02.2020]

[143] Forschungsstelle für Energiewirtschaft, https://fsr.eui.eu/eu-electricity-network-codes, [Accessed 09.01.2020]

[144] Meeus, L., Reif, V. 2020. Why did we start with electricity markets in Europe?. In *The Evolution of Electricity Markets in Europe*, Cheltenham, UK: Edward Elgar Publishing. Available From: Elgar Online: The online content platform for Edward Elgar Publishing<https://doi.org/10.4337/9781789905472.00013> [Accessed 14.02.2020]

Long-term markets (forward energy markets, forward transmission markets and capacity mechanisms)

Forward energy markets start from more or less four years up to one month before delivery. A financial exchange organises trade using standardised products, or market parties can make bilateral over the counter (OTC) deals. The negotiated energy prices are denominated per bidding zone, which in most cases overlap with national borders. The market considers a bidding zone as a copper plate. The figure below shows the current bidding zone configuration in Europe. If a market party wants to hedge prices across bidding zones, long-term cross-zonal transmission rights need to be acquired separately on the Joint Allocation Office (JAO) platform.[145] The platform is a joint service company of TSOs. The Forward Capacity Allocation Guideline (FCA GL)[146] regulates the allocation and calculation rules for cross-zonal transmission rights.[147]

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[145] Joint Allocation Office (JAO) is a service company that facilitates the electricity market by organizing auctions for cross border transmission capacity. On the 1st of October 2018, JAO became the Single Allocation Platform (SAP) for all European Transmission System Operators (TSOs) that operate in accordance to EU legislation, since it is able to implement and fulfil all regulatory obligations and requirements. JAO performs long- and short-term auctions of transmission capacity. JAO can offer annual, non-calendar annual, half-yearly, quarterly, monthly, weekly, weekend, daily and intra-day auctions. TSOs and Regulatory Authorities decide what auctions are performed on individual borders. Next to this JAO provides administrative and settlement services to TSOs and acts as a fall-back for the European Market Coupling.

[146] Commission Regulation (EU) 2016/1719 of 26 September 2016 establishing a guideline on forward capacity allocation (Text with EEA relevance) C/2016/5946, ELI: http://data.europa.eu/eli/reg/2016/1719/oj [Accessed 17.12.2019]

[147] Meeus, L., Reif, V. 2020. Why did we start with electricity markets in Europe? In *The Evolution of Electricity Markets in Europe*, Cheltenham, UK: Edward Elgar Publishing. Available From: Elgar Online: The online content platform for Edward Elgar Publishing<https://doi.org/10.4337/9781789905472.00013> [Accessed 14.02.2020]

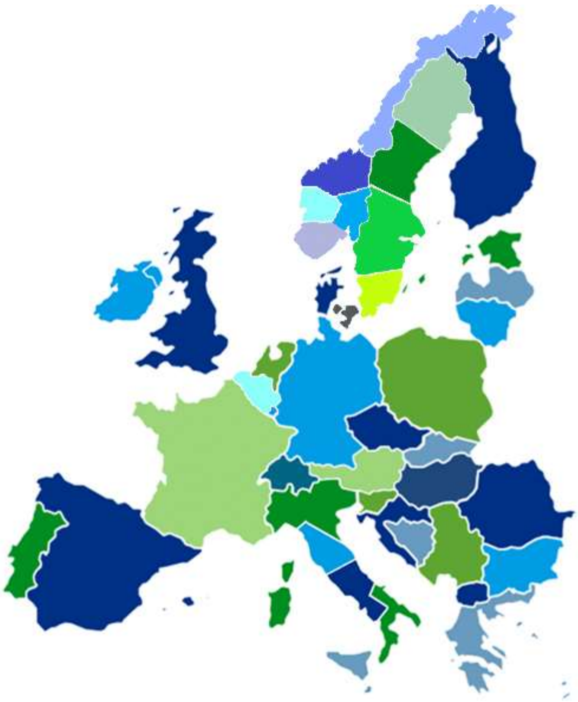

Figure 2.2 **The bidding zone configuration in Europe in September 2020**[148]

Besides forward energy and forward transmission markets, in the longer-term timeframe, Member States can decide to set up a capacity mechanism if deemed needed for adequacy reasons. Capacity mechanisms exist in many forms and are often organised by the TSO. The capacity procurement takes place one to about four years before delivery.

Wholesale or spot markets (day-ahead and intraday markets)

There is no obligation for market parties to buy and sell their energy on the spot market. Spot markets are often used to adjust long-term positions closer to delivery. Importantly, although volumes traded in the wholesale markets are, in some cases, only a fraction of the final volume of generated electricity, the wholesale prices serve as the price reference in long-term contracts.

The day-ahead market consists of one pan-European auction at noon for the 24 hours of the next day. All accepted bids are paid the marginal offer. Trading is organised by one or several power exchanges (PXs) per Member State[149]. Recently, it has been decided that the future intraday European model will consist of a combination of continuous trading with three European-wide auctions at pre-defined times.

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[148] Meeus, L., Reif, V. 2020. Why did we start with electricity markets in Europe? In *The Evolution of Electricity Markets in Europe*, Cheltenham, UK: Edward Elgar Publishing. Available From: Elgar Online: The online content platform for Edward Elgar Publishing<https://doi.org/10.4337/9781789905472.00013> [Accessed 14.02.2020]

[149] Nord Pool maximum NTC: [Online]. Available at: https://www.nordpoolspot.com/globalassets/download-center/tso/max-ntc.pdf [Accessed 12.10.2019]

The focus of this Thesis is on the short-term market mechanisms. The short-term mechanisms considered in this Thesis are defined as those that take place from the day-ahead until delivery hour, i.e. the day-ahead and intraday markets, and actions that are necessary for system balancing and congestion management.

Electricity prices in European day-ahead markets fell significantly by an average of 26 % in 2020 compared with the previous year. The Covid-19 pandemic led to a reduction in demand for electricity in many countries.[150] In combination with very low fuel prices, this led to reduced electricity prices. Figure 2.3 shows the average day-ahead electricity prices for 2019 and 2020 for 26 different European countries. In each of the countries studied, there was a reduction in electricity prices in 2020. Norway saw the largest decrease of 76 %, while in Poland the price decreased by only 12 %. In principle, different electricity price levels can also be seen in the various countries, because of the different compositions of the energy systems with regard to conventional power plants and renewable energies.

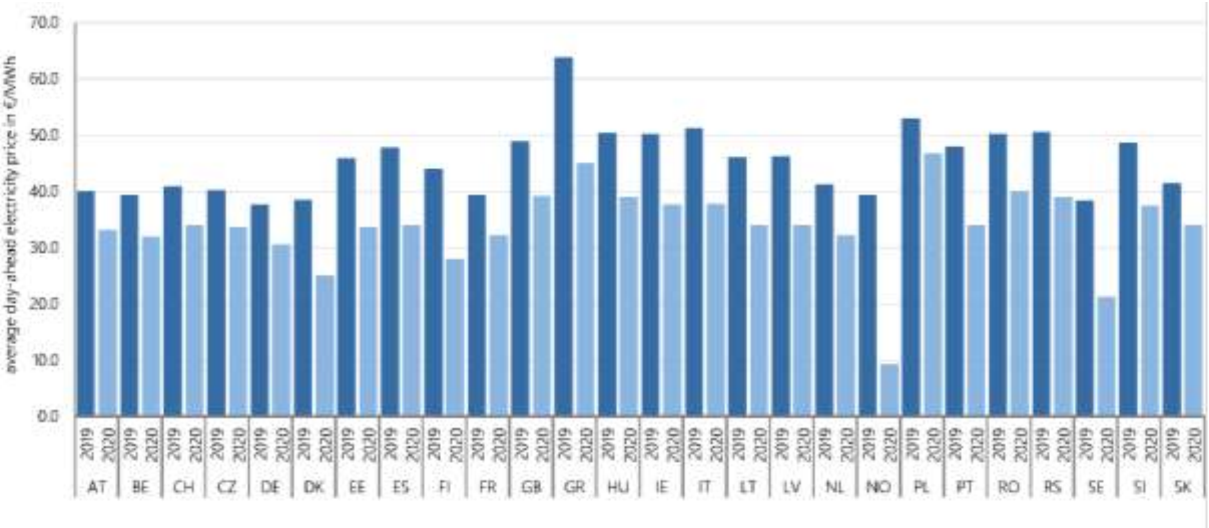

Figure 2.3 **Average day-ahead electricity prices in 26 European countries for the years 2019 and 2020**[151]

In line with the reduction in average electricity prices, there was also an accumulation of negative prices in 2020, some of which increased sharply. Negative prices mean that an electricity producer does not receive any remuneration for electricity generated, but actually has to pay for sold electricity. Renewables that receive subsidies have negative marginal costs, so they only stop generating electricity when prices are negative by the amount of their subsidy.

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[150] ENTSO-E. 2019. Vision on Market Design and System Operation towards 2030, Technical Report, European Network of Transmission System Operators for Electricity, URL: https://vision2030.entsoe.eu/wp-content/uploads/2019/11/ entsoefp_vision_2030_web.pdf. [Accessed 12.10.2019]

[151] ENTSO-E. 2020. Transparency Platform. Day-ahead Prices, https://transparency.entsoe.eu/transmission-domain/r2/dayAheadPrices [Accessed 12.10.2019]

Furthermore, inflexible conventional power plants cause negative prices, since it is more economical to continue producing instead of accepting an expensive shutdown and start-up process.[152]

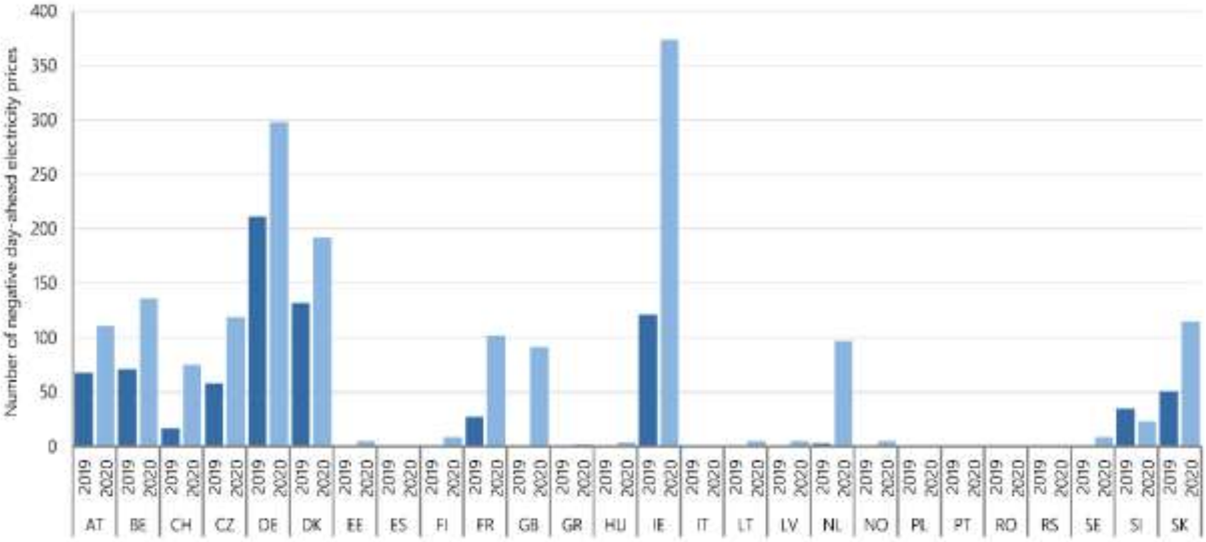

Figure 2.4. **Number of negative day-ahead electricity prices in 26 European countries for the years 2019 and 2020, based on data of entso-e**[153]

Figure 2.4 presents the number of negative prices in 2019 and 2020 for the 26 countries studied. In 19 of the 26 countries, there was an increase in the number of hours with negative prices. Only in Slovenia (SI) were 12 fewer hours with negative prices registered. In particular, there was an increase in hours with negative electricity prices in Ireland (IE, +253h), the Netherlands (NL, +94h), Great Britain (GB, +90h) and Germany (DE, +87h).

Hours with atypically high prices have been distinguished. For example, in 2019, in general, especially high prices were relatively rare and 92.4 % of hours did not exceed 50 € / MWh. The most frequently observed (~ 29.3 % of hours) price was ~ 25–33 € / MWh, followed by prices in the range of ~ 33–41 € (25.8 %) and ~ 41–50 € / MWh (19.9 %).

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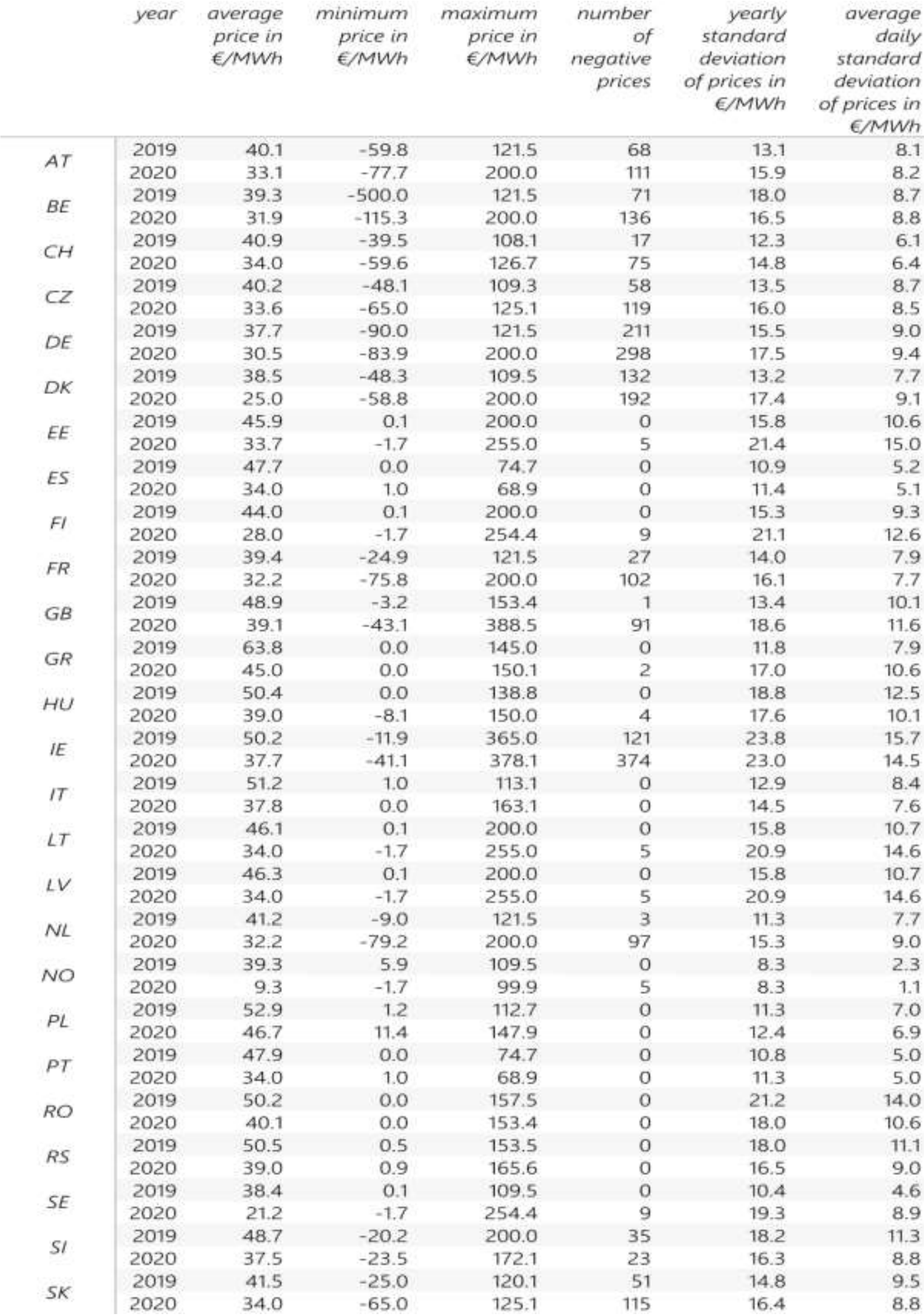
[152] ENTSO-E. 2020. Transparency Platform. Day-ahead Prices, https://transparency.entsoe.eu/transmission-domain/r2/dayAheadPrices [Accessed 12.10.2019]

[153] European Network of Transmission System Operators for Electricity ENTSO-E Transparency Platform. 2020. Day-ahead Prices, https://transparency.entsoe.eu/transmission-domain/r2/dayAheadPrices] [Accessed 10.04.2020]

Table 2.1

Statistical analysis of European day-ahead electricity markets[154]



	year	average price in €/MWh	minimum price in €/MWh	maximum price in €/MWh	number of negative prices	yearly standard deviation of prices in €/MWh	average daily standard deviation of prices in €/MWh
AT	2019	40.1	-59.8	121.5	68	13.1	8.1
	2020	33.1	-77.7	200.0	111	15.9	8.2
BE	2019	39.3	-500.0	121.5	71	18.0	8.7
	2020	31.9	-115.3	200.0	136	16.5	8.8
CH	2019	40.9	-39.5	108.1	17	12.3	6.1
	2020	34.0	-59.6	126.7	75	14.8	6.4
CZ	2019	40.2	-48.1	109.3	58	13.5	8.7
	2020	33.6	-65.0	125.1	119	16.0	8.5
DE	2019	37.7	-90.0	121.5	211	15.5	9.0
	2020	30.5	-83.9	200.0	298	17.5	9.4
DK	2019	38.5	-48.3	109.5	132	13.2	7.7
	2020	25.0	-58.8	200.0	192	17.4	9.1
EE	2019	45.9	0.1	200.0	0	15.8	10.6
	2020	33.7	-1.7	255.0	5	21.4	15.0
ES	2019	47.7	0.0	74.7	0	10.9	5.2
	2020	34.0	1.0	68.9	0	11.4	5.1
FI	2019	44.0	0.1	200.0	0	15.3	9.3
	2020	28.0	-1.7	254.4	9	21.1	12.6
FR	2019	39.4	-24.9	121.5	27	14.0	7.9
	2020	32.2	-75.8	200.0	102	16.1	7.7
GB	2019	48.9	-3.2	153.4	1	13.4	10.1
	2020	39.1	-43.1	388.5	91	18.6	11.6
GR	2019	63.8	0.0	145.0	0	11.8	7.9
	2020	45.0	0.0	150.1	2	17.0	10.6
HU	2019	50.4	0.0	138.8	0	18.8	12.5
	2020	39.0	-8.1	150.0	4	17.6	10.1
IE	2019	50.2	-11.9	365.0	121	23.8	15.7
	2020	37.7	-41.1	378.1	374	23.0	14.5
IT	2019	51.2	1.0	113.1	0	12.9	8.4
	2020	37.8	0.0	163.1	0	14.5	7.6
LT	2019	46.1	0.1	200.0	0	15.8	10.7
	2020	34.0	-1.7	255.0	5	20.9	14.6
LV	2019	46.3	0.1	200.0	0	15.8	10.7
	2020	34.0	-1.7	255.0	5	20.9	14.6
NL	2019	41.2	-9.0	121.5	3	11.3	7.7
	2020	32.2	-79.2	200.0	97	15.3	9.0
NO	2019	39.3	5.9	109.5	0	8.3	2.3
	2020	9.3	-1.7	99.9	5	8.3	1.1
PL	2019	52.9	1.2	112.7	0	11.3	7.0
	2020	46.7	11.4	147.9	0	12.4	6.9
PT	2019	47.9	0.0	74.7	0	10.8	5.0
	2020	34.0	1.0	68.9	0	11.3	5.0
RO	2019	50.2	0.0	157.5	0	21.2	14.0
	2020	40.1	0.0	153.4	0	18.0	10.6
RS	2019	50.5	0.5	153.5	0	18.0	11.1
	2020	39.0	0.9	165.6	0	16.5	9.0
SE	2019	38.4	0.1	109.5	0	10.4	4.6
	2020	21.2	-1.7	254.4	9	19.3	8.9
SI	2019	48.7	-20.2	200.0	35	18.2	11.3
	2020	37.5	-23.5	172.1	23	16.3	8.8
SK	2019	41.5	-25.0	120.1	51	14.8	9.5
	2020	34.0	-65.0	125.1	115	16.4	8.8

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[154] Forschungsstelle für Energiewirtschaft, https://www.ffegmbh.de/, [Accessed 12.10.2021]:

However, the price over 50 € / MWh was only 671 hours or 7.6 % of the year, including higher than 100 € / MWh only 105 hours or 1.2 %, over 150 € / MWh – 39 hours or 0.4 %. The highest prices – over 200 € / MWh – were only 19 hours or 0.2 % of the whole year.

Wholesale of Electricity on the Nord Pool Exchange

Electricity wholesale in Latvia takes place on the Nord Pool[155] electricity exchange, where the Latvian trading area was opened on 3 June 2013 for the next day's electricity market (Elspot) and on 10 December 2013 for the current day's market (Elba)[156]. As practically all electricity-trading transactions in the Latvian area are performed in the next day market[157], only the Elspot market is considered in the following analysis. In terms of energy sold, Nord Pool is the largest power exchange in Europe, currently operating in the Nordic countries (Norway, Denmark, Sweden, Finland), the Baltic countries (Estonia, Latvia, Lithuania), as well as Germany and the United Kingdom.

Nord Pool is owned by the Nordic transmission system operators Statnett SF, Svenska kraftnät, Fingrid Oyj, Energinet.dk and the Baltic transmission system operators Elering, Litgrid and Augstsprieguma tīkls (AST)[158]. The large number of participants ensures high market liquidity and, consequently, the lowest possible costs for purchasing electricity on the stock exchange.[159]The electricity market price, also known as the Nord Pool system price, is determined according to the intersection of the supply and demand curves, which is the equilibrium point of the market (Figure 2.5).

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[155] http://nordpoolspot.com/

[156] https://www.sprk.gov.lv/uploads/doc/LemumsN146D03122015.pdf

[157] 99.8% of the amount of electricity purchased in Latvia and 98.1% of the amount of electricity sold by Latvian producers in 2019.

[158] Nord Pool. About Us. [Online] [Cited: 13.05.2020.] https://www.nordpoolgroucom/about-us.

[159] Baltputnis, K. 2020. Decision-Making Support Methods, Algorithms and Tools for Electricity Market Participants. Doctoral Thesis. Riga: RTU Press, 117

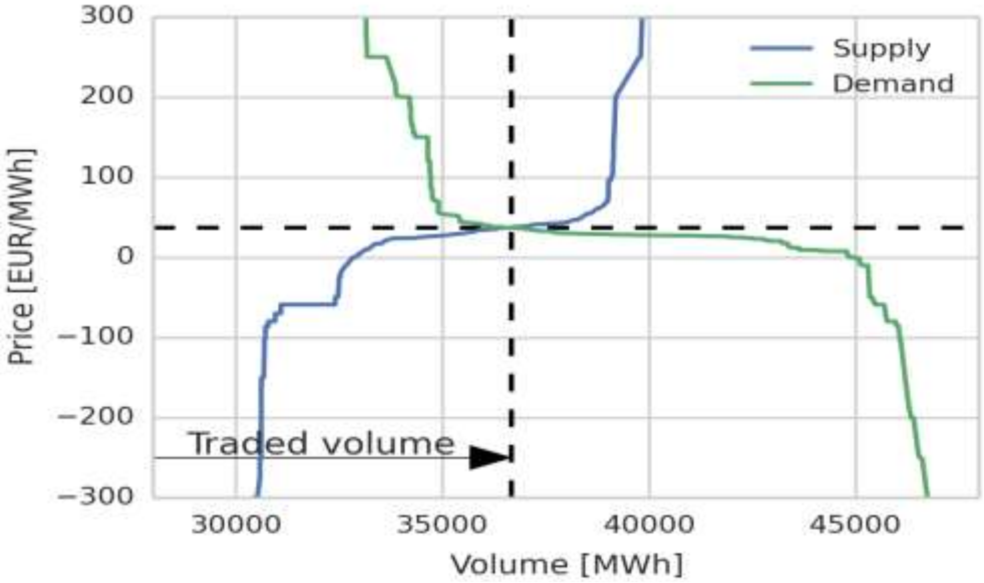

Figure 2.5 **Example of supply and demand curves for one hourly product (14:00 – 15:00) on 07.05.2016**[160]

Demand and supply must therefore constantly be balanced for system stability. The electricity demand is also inelastic over short period of times, resulting in high volatility and non-stationary prices.[161] For the next day's market, these curves are created the day before, summarizing for each hour separately the electricity sales and purchase offers submitted by the exchange participants according to the announced price and volume. By ranking all the offers in ascending order by price, an economic profitability curve is obtained. It should be noted that Nord Pool has restrictions on electricity price offers: it may not be lower than -500 € / MWh and higher than 3000 € / MWh. It is worth mentioning that there could exist a significant number of variables affecting the market equilibrium, and at the same time some of these lack information.

However, the full pricing algorithm is more complex, as participants can submit three different types of bids and requests to the exchange[162]: not only hourly bids (which account for the majority of the next day's market), but also related bids (for at least three consecutive hours) and flexible bids (the participant indicates only the number of hours, but the specific position in the daily schedule is determined by the market operator). The flow of energy on interconnections with neighbouring Nord Pool members must also be taken into account.[163]

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[160] Knaut, A., Paulus, S. 2016. Hourly price elasticity pattern of electricity demand in the German day-ahead market, EWI Working Paper, No. 16/07, Institute of Energy Economics at the University of Cologne (EWI), Köln

[161] Cerjan, M., Krželj, I., Vidak, M., and Delimar, M. 2013. A literature review with statistical analysis of EPF methods. In Eurocon, 756–763. https://doi.org/10.1109/EUROCON.2013.6625068 [Accessed 12.10.2019]

[162] http://www.nordpoolspot.com/TAS/Day-ahead-market-Elspot/Order-types [Accessed 10.07.20]

[163] Baltputnis, K. 2020. Decision-Making Support Methods, Algorithms and Tools for Electricity Market Participants. Doctoral Thesis. Riga: RTU Press, 117 [Accessed 12.10.2020]

The basic principle of the stock Exchange's operation in accordance with economic profitability determines that those producers who offer the lowest electricity generation price for the requested amount cover the demand for electricity. In an efficient market, the equilibrium price corresponds to the variable cost of production of the most expensive unit of generation assumed. In turn, these costs mainly consist of the fuel, emissions and operating costs of the most expensive power plant per unit of electricity produced.[164]

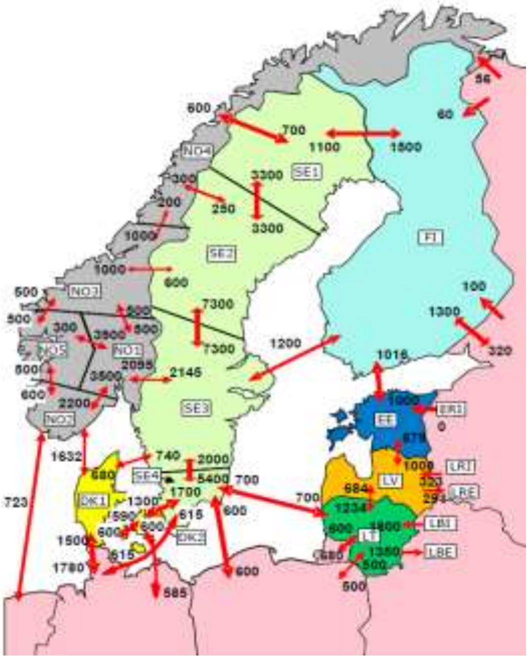

Figure 2.6 **Nord Pool sales areas and maximum interconnection capacity (MW)**[165]

The resulting price for the Nord Pool system also serves as a reference point for electricity futures and forwards contract trading, but to get real the next day's market hourly price in each Nord Pool shopping area required also comply with the restricted transmission line throughput between them. Although, the functioning of the market is based on demand satisfaction of the lowest possible costs, physically exist in the energy system restrictions on the transmission of electricity from one area to another, which can therefore also limit all necessary cheaper electricity imports in another area. In this case, the need arises in this area activate another generation source with higher costs. As a result, electricity the price in the “deficit” area increases, but in an area with a “surplus” of energy decreases until transmission, restrictions are fulfilled. Thus, if the interconnection between the capacity of areas is fully utilized, different price zones are usually formed.

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[164] Baltputnis, K. 2020. Decision-Making Support Methods, Algorithms and Tools for Electricity Market Participants. Doctoral Thesis. Riga: RTU Press, 117 [Accessed 12.10.2020]

[165] Nord Pool maximum NTC: https://www.nordpoolspot.com/globalassets/download-center/tso/max-ntc.pdf [Accessed 10.07.20]

According to Baltputnis, it can be concluded that electricity day-ahead market price in the Latvian bidding area has the strongest positive correlation with consumption and production in Latvia and Lithuania, as well as the production from certain types of energy sources – Baltic natural gas and oil shale plants, Kruonis PSHP and Nordic HPPs. In other words, larger consumption is met by larger production, which increases the market clearing price, and thus allows the activation of production plants with higher marginal costs. The price in the Latvian bidding area is very strongly correlated with the price in the Lithuanian area, and strong correlation is also with Estonia and Finland, moderate – with Sweden. Electricity market flow from Finland and Estonia to Latvia aids in decreasing the price, whereas the flow from Latvia to Lithuania, increases it.[166]

VRE influences to wholesale energy prices

According to[167],[168] wind and solar photovoltaics, have four somewhat-unique characteristics that can influence wholesale market prices and generation assets. First, weather-driven variability in electricity production, which can affect energy and capacity markets as well as ramping and ancillary service needs. Then, uncertainty in forecasts of future output, which can impact ancillary service needs and costs; also, resource-driven location dependencies that, in some cases, can impact the need for or benefit of new transmission investment, and finally, low, or even negative marginal costs, which tend to place VRE before resources in the dispatch merit order.

In order to understand the essence of the problem the factors influencing electricity exchange price in EU Latvia been analysed.

As mentioned, electricity wholesale in Latvia takes place on the Nord Pool[169] electricity exchange, where the Latvian trading area was opened on 3 June 2013 for the next day's electricity market (Elspot) and on 10 December 2013 for the current day's market (Elbas)[170]. As practically all electricity trade transactions in the Latvian area are performed in the next day market, only the Elspot market is considered in the following analysis.

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[166] Baltputnis, K., 2020. Decision-Making Support Methods, Algorithms and Tools for Electricity Market Participants, Promocijas darba kopsavilkums, https://doi.org/10.7250/9789934225093 [Accessed 12.10.2019]

[167] Wiser, R. H., et al. 2017. *Impacts of variable renewable energy on bulk power system assets, pricing, and costs*. Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), Volume 120, 2020, 109670, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2019.109670. [Accessed 03.06.2020] (https://www.sciencedirect.com/science/article/pii/S1364032119308755) [Accessed 12.10.2019]

[168] Hirth, L. 2013. The market value of variable renewables: The effect of solar wind power variability on their relative price. *Energy economics*, 38, 218–236. 10.1016/j.eneco.2013.02.004 [Accessed 10.10.2019]

[169] Nord Pool maximum NTC: [Online]. Available at: https://www.nordpoolspot.com/globalassets/download-center/tso/max-ntc.pdf) [Accessed 12.10.2019]

[170] Nord Pool [Online]. Available at: http://http://nordpoolspot.com/historical-market-data/ [Accessed 12.10.2019]

Comparing the correlations with the wholesale price of electricity in the Nord Pool Latvian trade area with various potentially influencing factors, it can be seen that the largest positive correlation is with the volume of consumption and development in Latvia and Lithuania, as well as with electricity generation from certain types of sources: mainly natural gas and oil shale thermal power plants in the Baltic States, Kroņi HPP and HPP[171]. In other words, as the total volume of consumption and generation increases, the price in the market increases. In turn, as the market price increases, certain types of power plants are started up. The price in Latvia has a high positive correlation with the price in the Lithuanian region[172]. This follows from the analysis of Nord Pool data from 2016 to 2020.

However, there are the increased amount (See Table 2.2) of renewable-based distributed energy resources (DERs) emerging on the demand side of grid. More often are mentioned renewable technology such as solar photovoltaic systems, wind generations, and electric vehicles, but also encompass other resource capacities such as demand response programs, batteries, micro grids, and small generators[173]. It is considered challenge by itself to integrate these new technology resources into existing infrastructure and energy markets, adding issues with intermittent nature of renewables DERs, which have the potential to jeopardize system stability.

Table 2.2

Total Installed Capacity of DER in Nord Pool area and interconnected zones 2020, MWh

2020	Wind Onshore, MW	Wind Offshore, MW	Solar, MW
LV	59	n/d	n/d
EE	329	n/d	123
LT	534	n/d	7
FI	2146	n/d	n/d
SE	9648	n/d	n/d
NO	3068	n/d	n/d
DE	53405	7709	46471

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[171] Viskuba K., Silinevicha V. 2021. Renewable Energy Sources in the Baltic States and New Business Approach of the Sector, *Vilnius University Open Series*, 120–127. doi: 10.15388/VGISC.2021.16. [Accessed 12.10.2019]

[172] Sauhatas, A., Baltputnis, K. 2017. *Price of Electricity and Its Influencing Factors* Riga Technical University. Academic Search Complete. [Online]. Available at: https://www.em.gov.lv/files/attachments/Elektroenergijas_cenu_petijuma_nosleguma_zinojums_2017-05-31.pdf... ID 25645. [Accessed 17.09.2019]

[173] Bird, L. Milligan, M., Lew, D. 2013. *Integrating Variable Renewable Energy: Challenges and Solutions; National Renewable Energy Laboratory*: Golden, CO, USA, [Online]. Available at: https://www.nrel.gov/docs/fy13osti/60451.pdf [Accessed 28.07.2020].

Table 2.2 continued

2020	Wind Onshore, MW	Wind Offshore, MW	Solar, MW
DK1	3645	1277	672
DK2	757	432	341
	16578	14	9438
BE	2248	1859	3887
NL	3973	1709	5710
LU	154	n/d	170
PL	5956	n/d	1310
UK	995	n/d	92
AT	3133	n/d	1333

Source: created by the author, using[174] data

In order to assess in more detail on the conditions under which a particularly high next day market price is formed in the Latvian trading area, hourly prices from 2016 to 2019 have been analysed (see Chapter 3). Hours with atypically high prices have been distinguished. For example, in 2019, in general, especially high prices were relatively rare and 92.4 % of hours did not exceed 50 € / MWh. The most frequently observed (~ 29.3 % of hours) price was ~ 25–33 € / MWh, followed by prices in the range of ~ 33–41 € (25.8 %) and ~ 41–50 € / MWh (19.9 %). However, the price over 50 € / MWh was only 671 hours or 7.6 % of the year, including higher than 100 € / MWh only 105 hours or 1.2 %, over 150 € / MWh – 39 hours or 0.4 %. The highest prices – over 200 € / MWh – were only 19 hours or 0.2 % of the whole year.

As have been mentioned before, the correlation with the wholesale price of electricity in the Nord Pool Latvian trade area with of generated wind energy is considered weak – 0.29. However, for hours with the highest prices situation considerably changes.

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[174] Nord Pool maximum NTC: [Online]. Available at: https://www.nordpoolspot.com/globalassets/download-center/tso/max-ntc.pdf [Accessed 28.07.2020]

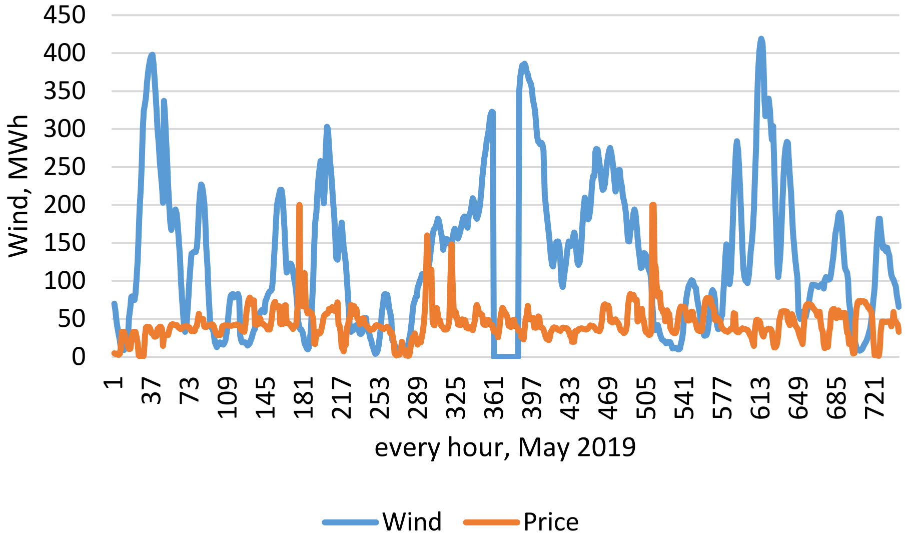

Figure 2.7 **Wind energy and day ahead electricity prices, May 2019**

Source: created by the author, using[175] data

Figure 2.7 shows that the highest prices above 200 € / MWh are observed in the hours with low wind generation.

Despite the different methodological approaches and the range of parameter assumptions applied, there appears to be broad consensus that higher levels of VRE will result in lower average wholesale electricity prices.[176] For example, according to [177] the change in average wholesale energy price ($ / MWh) that corresponds with a 1 % increase in VRE penetration is -$0.15, very close results show also[178] estimations – accordingly -$0.10 with wind penetration and -$0.13 for solar energy. Estimations in [179] and [180] for wind energy are -$0.25 and -$0.28 accordingly. However, results of investigations [181] and [182] show increasing change in average wholesale energy price – $0.41and -$0.52.

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[175] Nord Pool maximum NTC: [Online]. Available at: https://www.nordpoolspot.com/globalassets/download-center/tso/max-ntc.pdf) [Accessed 12.10.2019]

[176] Hirth, L. 2013. The market value of variable renewables: The effect of solar wind power variability on their relative price. *Energy economics*, 38, 218–236. 10.1016/j.eneco.2013.02.004) [Accessed 12.10.2019]

[177] Brancucci M.-A. C., Brinkman, G., and Hodge B.-M. 2016. The Impact of Wind Power on Electricity Prices. *Renewable Energy* 94 (August): 474–87. https://doi.org/10.1016/j.renene.2016.03.053.) [Accessed 16.10.2019]

[178] Mills, A. D., Wiser, R. H., Seel, J. 2017. *Power plant retirements: Trends and possible drivers*. Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States),

[179] Deetjen, T. A. et al. 2016. Solar PV integration cost variation due to array orientation and geographic location in the Electric Reliability Council of Texas. *Applied Energy*, 180: 607-616.

[180] Fagan, B. et al. 2012. The potential rate effects of wind energy and transmission in the Midwest ISO region. *Synapse*, *May*, 2012, 22.

[181] Levin, T., Botterud, A. 2015. Electricity market design for generator revenue sufficiency with increased variable generation. *Energy Policy*, 87: 392–406. 10.1016/j.enpol.2015.09.012) [Accessed 12.10.2019]

[182] Frew, B. et al. 2016. *Impact of Market Behavior, Fleet Composition, and Ancillary Services on Revenue Sufficiency*. National Renewable Energy Lab.(NREL), Golden, CO (United States),

Analysis of the main economic indicators of the industry

The author shows basic indicators of the sector in Latvia for the past few years, basing the information on statistical data analyses. In the previous researches and publications[183] the author has already explored main indicators of Latvian energy sector, but, in author's view, it is valuable to observe data updates, because this is the way how we can see the most recent changes, respond to the changes and make more precise future prognosis. The average contribution of the energy industry to the national GDP is not particularly changed and is 2.11 % during the 2013–2019 period. Latvia is one of those countries that are strongly relying to imported energy resources from other countries, because Latvia is not able to fully meet the necessary electricity consumption.

Author began with the industry contribution to one of the most important indicators of the country's economic development – gross domestic product. Although GDP is commonly used at constant prices, considering inflation, to compare the volume of goods and services, the author has examined the contribution of industry to GDP in real (average) prices, which includes changes in output and price.

There are three main sources of electricity generation in Latvia – hydroelectric power stations, large cogeneration units and other cogeneration units. To a much lesser extent, electricity is generated from small hydro, wind and biogas plants. This fact confirms the promising growth and development of this industrial sector, however former potential was considered restricted.

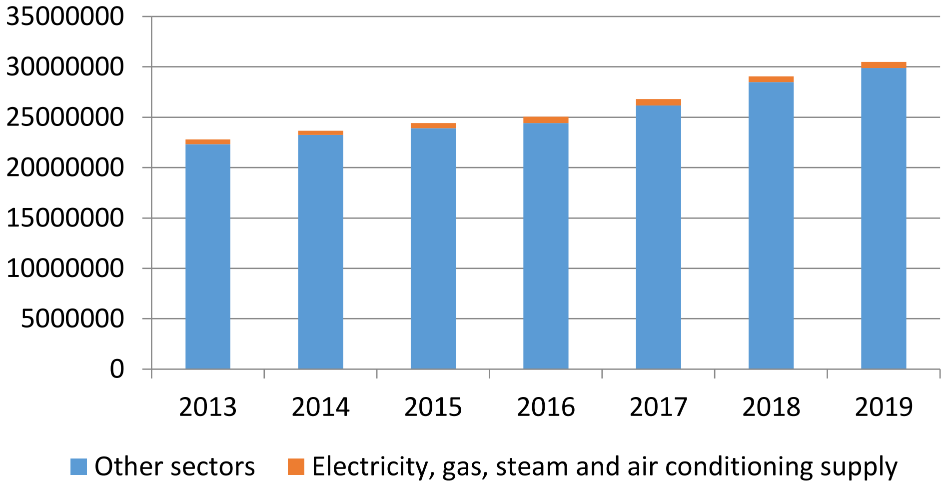

Figure 2.8 **Electricity, Gas, Steam and Air Conditioning Supply Share in Latvia's GDP 2013–2019 years, real prices, '000 EUR**

Source: created by the author, using[184] data

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[183] Viskuba, K., Silinevicha, V. 2020. Wind Farm Project Results and Innovative Business Models. Humanities and Social Sciences: Latvia. Volume 28, Issue 1. ISSN 1022-4483. 5–29

[184] Central Statistical Bureau of Latvia. URL: www.csb.gov.lv) [Accessed 27.12.2019]

Figure 2.8 shows the share of electricity, gas, heating and air conditioning in the GDP of Latvia in the period 2013-2019. The graph is in absolute terms, but the author has given a percentage to make it easier to understand the sector's share of GDP. Summarizing the results, it can be stated that the average contribution of the industry to the national GDP is 2.23 % during the five years given. The largest increase was in 2016, from 2.09 % share in 2015 to 2.55 % in 2016. Industry made the smallest contribution to GDP in 2014, calculated 1.78 % in total volume that year. The sector's contribution to Latvia's GDP has been stable over the years, with positive growth prospects.[185]

The most significant sources of electricity generation in Latvia are the Riga natural gas combined heat and power plants TEC-1 and TEC-2, with a total installed electrical capacity of 976 MW in 2019, and the Daugava cascade hydro power plants (HPPs) with an installed capacity of 1558 MW[186]. The total installed electrical capacity in Latvia was 2915 MW in 2019; other RES power plants, excluding Daugava HPP, make up just 9 % (wind, small hydropower, solar power plants, and biomass and biogas cogeneration plants)[187]. The Daugava HPPs have a high proportion of installed capacity, but considering their fluctuating generation, which is significantly dependent on climatic conditions, natural gas cogeneration plants still play an important role in Latvia’s energy supply. In 2017, under favourable conditions for the operation of HPPs, the local generation covered Latvia’s electricity consumption at the amount of 101 %, while in 2019, under significantly less favourable conditions, only at the amount of 84.7 %[188]. It follows from the above that electricity production in Latvia is characterized by low diversification of energy sources, which significantly affects self-sufficiency in energy dependence on imported fossil sources[189].

The production and consumption of energy resources is a major factor in the global economy. The energy sector is stimulated by global energy supply and demand. Latvia belongs to those countries that are heavily dependent on imported energy resources because they are unable to fully meet the required electricity consumption. The volumes of electricity import, export and consumption in Latvia for the period 2014–2019 were defined.

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[185] Viskuba, K., Silinevicha, V. 2020. Wind Farm Project Results and Innovative Business Models. Humanities and Social Sciences: Latvia. Volume 28, Issue 1. ISSN 1022-4483. 5–29

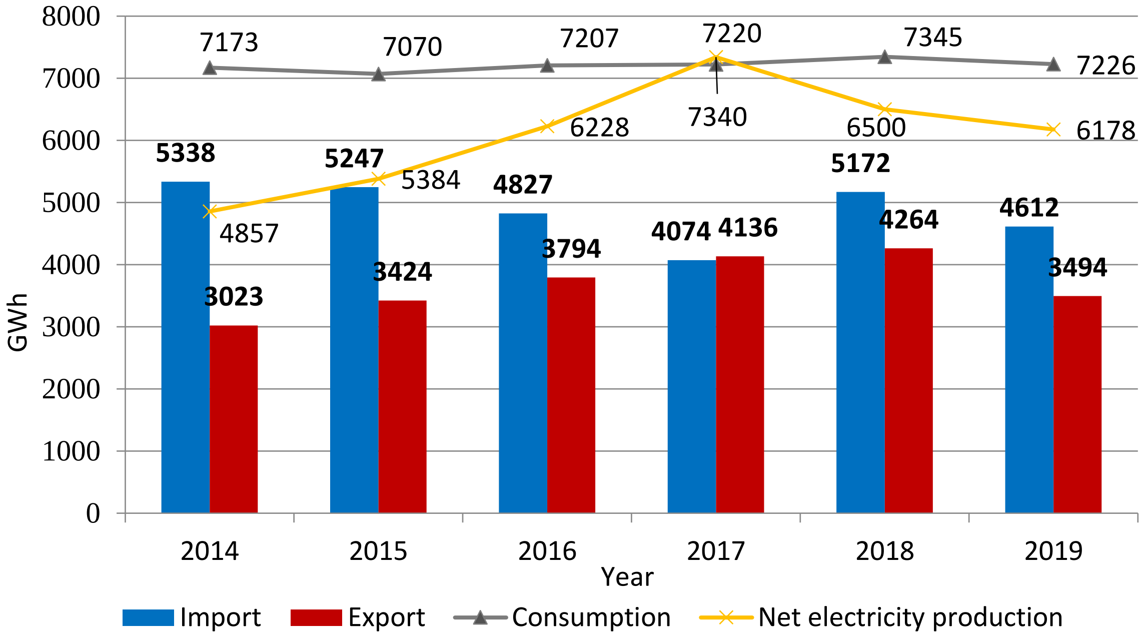
[186] European Commission: Energy. Latvian Ministry of Economics: Latvia’s National Energy and Climate Plan 2021–2030. Available online: https://ec.europa.eu/energy/sites/ener/files/documents/ec_courtesy_translation_lv_necpdf [Accessed 05.01.2021]

[187] Latvenergo Group: Facts. Available online: https://latvenergo.lv/en/par-mums/razosana [Accessed 18.03.2021]

[188] Central Statistical Bureau of Latvia: Electricity Production, Imports, Exports and Consumption. Available online: https: //stat.gov.lv/en/statistics-themes/business-sectors/energy [Accessed 18.03.2021]

[189] European Commission: Energy. Latvian Ministry of Economics: Latvia’s National Energy and Climate Plan 2021–2030. Available online: https://ec.europa.eu/energy/sites/ener/files/documents/ec_courtesy_translation_lv_necpdf [Accessed 18 March 2021]

The data of Latvian total electricity demand, net electricity production, import and export for the period 2014–2019 is shown on Figure 2.9. There have been no significant fluctuations in final energy consumption over the last decade, moreover, the usage of electricity in 2020 decreased due to the coronavirus crisis (in mid-March, in the Baltic States was declared a state of emergency to limit the spread of the Covid-19 pandemic, which affected electricity demand, especially in the segment of legal entities). In conjunction with the generation increase, the export of electricity has also mostly increased (the correlation of net electricity production and export is notable on the graph). The electricity import is volatile, during the researched time period, however, it is partly relating to export changes. It should be noted that Latvia's export exceeded import in 2017. That year, Latvian domestic electricity production covered 101 % of consumption.



Source: created by the author, using [190] data

Figure 2.9 **Latvia's Electricity Import, Export, Consumption and Net Electricity Production 2014–2019 years, GWh**

Source: created by the author, using [191] data

In 2017, compared to 2016, import fell by 15.6 %, export increased by 9 %, consumption grew by 1.7 %. The main reason of such export increase was the increase in electricity generation at the Daugava HPP. It has been driven by a larger inflow of water into the Daugava,

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[190] Central Statistical Bureau of Latvia: Electricity Production, Imports, Exports and Consumption. Available online: https: //stat.gov.lv/en/statistics-themes/business-sectors/energy [accessed on 18 March 2021]

[191] Central Statistical Bureau of Latvia. URL: www.csb.gov.lv [Accessed05.01.2021]

and thus electricity generation in 2017 has been the largest since 1998, as well as the third largest in the history since 1966. As JSC *"Latvenergo"* mentioned in "Sustainability and Annual Report 2017", hydropower plants (HPP) production increased by 74 % in 2017, because of this, the production of fossil fuel power station decreased by 36 %. In 2019, Latvia's total net electricity production was by 5 % lower than in 2018, logically followed by a decline in exports. Moreover, the decrease was also observed in total consumption and import of 2019. It can be explained by active implementation of energy efficiency policy, as well as, climate changes.

The main types of RES in Baltics are hydropower, wind, solar, biomass and waste. The author considers that an installed capacity is showing a full clean potential of each country, which, in opposite to total generation, is not influenced by short term technical issues, market volatility, water inflow and so on. According to the ENTSO-E,[192] the total installed capacity of Latvia's hydropower plants was 1537 MW in 2015, it increased by 2 MW in 2017 and remains the same until 2019. The low increase can be explained by long, technically difficult and financially expensive work process. Daugava HPP is the largest hydropower plant in the country, which provides a high share of renewable energy and is one of the most important reasons that allows Latvia to be among the greenest countries in the EU for a long time. Lithuania's hydropower total installed capacity in explored time period has not changed and is 1028 MW in 2019. Lithuania has two main hydropower generation sources- the first is hydro pumped storage plant Kruonis with 900 MW installed capacity and Kaunas hydroelectric plant with 101 MW installed capacity. The work of these two plants is connected, because the Kaunas reservoir is acting as the lower reservoir for the Kruonis HPSP. Estonia's total installed capacity is only 8 MW, what can be explained by geographical area of Estonia, the rivers are short and mostly have small discharge.

Turning to the Latvia's development trends of renewable energy sources, the author wishes to mention the topical issues of RES defined by Latvian Wind Energy Association[193], which mentions two factors: "Latvia's great dependence on energy resources from Russia and the desire of the country to increase self-sufficiency and independence in this area; There is a tendency in the world, and especially in Europe, to increase the use of green or renewable energy in our daily lives."

The use of wind resources is the second largest form of electricity generation in Europe. On average, wind farms in the EU operate at 35 % onshore and 50 % offshore, with total installed wind turbines of approximately 178.8 GWh in 2018.

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[192] European Network of Transmission System Operators for Electricity. URL: https://www.entsoe.eu

[193] Wind energy association, https://wea.lv/en/wind-energy/#news [cit. 23.08.2018]

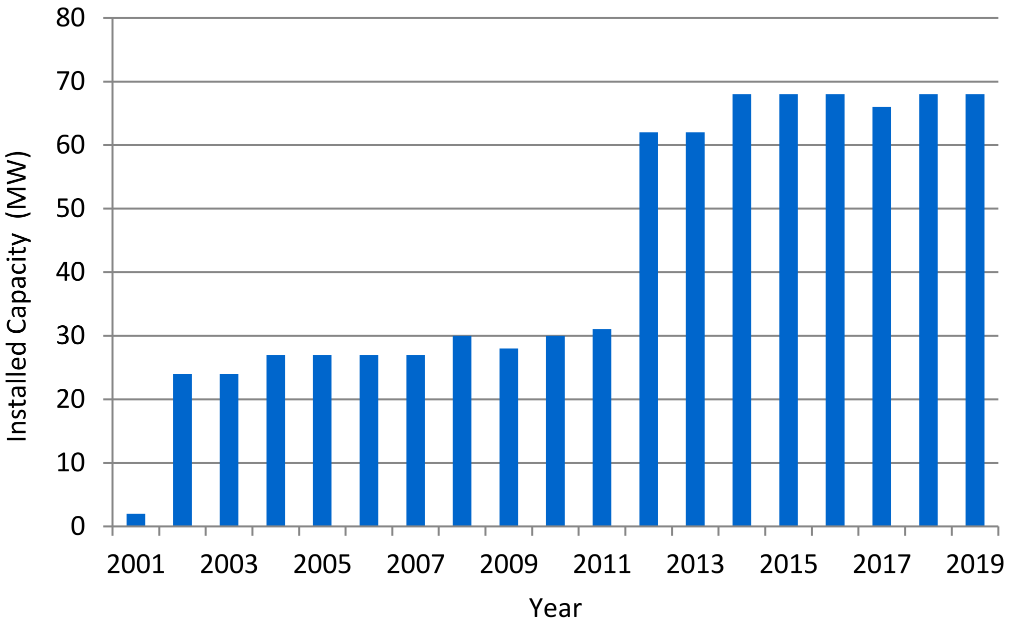

Figure 2.10 **Total Installed Capacity of Latvia's Wind Turbines in 2001–2019, MWh**

Source: created by the author, using[194] data

The first wind generators in Latvia were installed in 1995, but their total installed capacity was insignificant. The total installed capacity in 2001 was only 2 MWh, but next year it increased significantly (to 24 MWh). The next leap was observed in 2012, when installed capacity increased rapidly to 62 MWh. This rapid increase can be explained by the start of exploitation period of several plants, including the producer Ltd. "*Winergy*", with installed capacity of 20.07 MW. (See Figure 2.10)

The total installed capacity of wind turbines in Latvia is now about 66 MWh, which allows to produce about 1.8 % of the electricity consumed. In contrast, in Estonia, the installed capacity is more than 300 MWh (about 8.5 % of electricity consumed) and in Lithuania more than 500 MWh (10.5 % of electricity consumed). (See Figure 2.11)

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[194] Nord Pool [Online]. Available at: http://http://nordpoolspot.com/historical-market-data/ [cit. 28.07.2020]

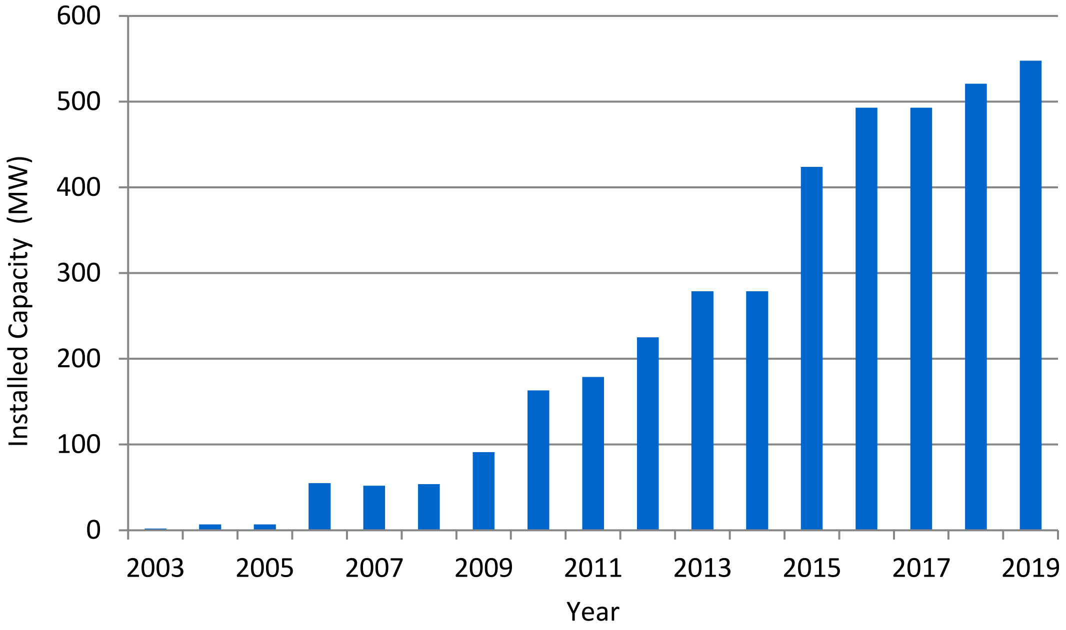

Figure 2.11 **Total Installed Capacity of Lithuania's Wind Turbines in 2001–2019, MWh**

Source: created by the author, using[195] data

The situation with wind power plants capacity is different and not only in total Baltic volumes, but in volumes of each country. In 2001 installed capacity of wind power plants was only 2 MW, but following next two years it substantially increased to 24 MW. The next leap when installed capacity increased rapidly to 62 MW in total was in 2012. It can be explained with the start of exploitation period of several wind farms, for instance, 20.07 MW of installed capacity by producer Ltd. "*Winergy*". Latvia's total installed capacity of wind turbines in 2019 was about 68 MW. In contrast, in Estonia the installed capacity in 2019 was 310 MW, which is 4.5 times higher than Latvia's. However, Lithuania is absolute leader between Baltic counties with 548 MW installed. (See Figure 2.12) According to the "National Energy and Climate Plan for 2021–2030"[196], which was prepared by The Ministry of Economics of the Republic of Latvia, Latvia plans to increase the share of RES in electricity generation by increasing the installed capacity of wind generators and solar photovoltaics, taking into account the capacity of Latvia's electricity transmission network, which currently allows to increase the amount of electricity transferred to the network by 800MW. Taking into account the considerations of maritime spatial planning, it is planned to develop joint offshore wind farms projects (with a maximum capacity of 800 MW) on the Latvian-Estonian border and the Latvian-Lithuanian

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[195] Nord Pool [Online]. Available at: http://http://nordpoolspot.com/historical-market-data/ [cit. 28.07.2020]

[196] Ministru kabineta 2020. gada 4. februāra rīkojums Nr. 46 Par Latvijas Nacionālo enerģētikas un klimata plānu 2021.–2030. gadam. https://likumi.lv/ta/id/312423

border.[197] The partnership process has already started on September 2020, when The Minister for Economics of Latvia and Estonian Economy and Infrastructure Minister have electronically signed a Memorandum of Understanding on the joint project of the Latvian and Estonian offshore wind farm for energy production from renewable energy sources.

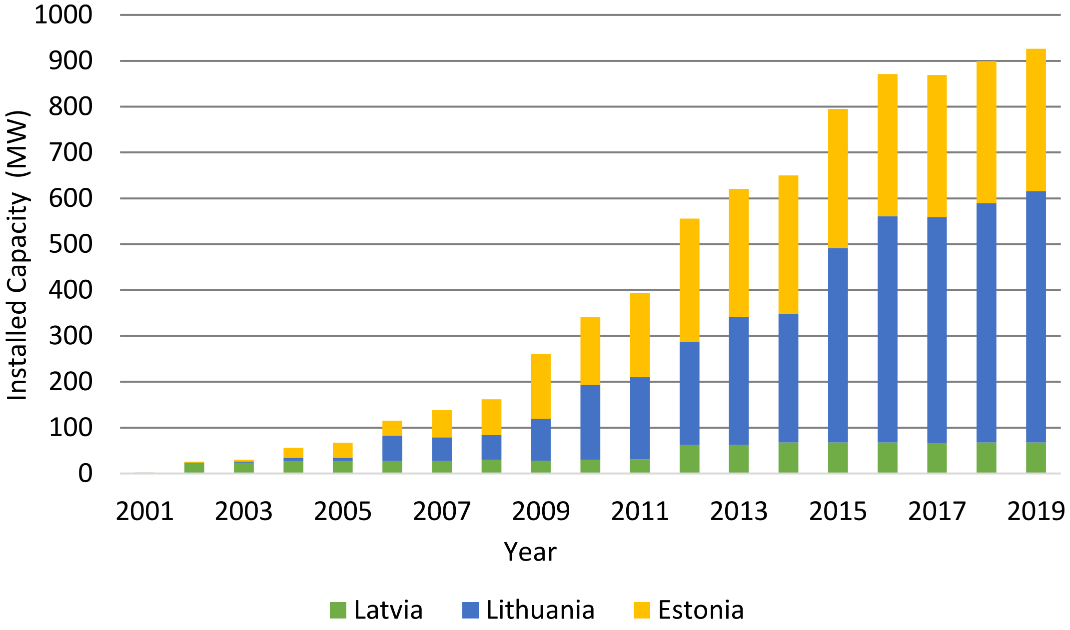

Figure 2.12. **Total Installed Capacity of Latvia's, Lithuania's and Estonia's Wind Turbines in 2001–2019, MW**

Source: created by the author, using[198] data

Other renewable energy sources are not that well developed and can be put in one group of "Other RES". This group in each country is different, it contains summarized installed capacities of different types of renewable energy sources (in Latvia 126 MW, Lithuania 199 MW, Estonia 221 MW of total installed capacity in 2021). According to ENTSO-E, in Latvia other RES consists only of biomass, but data[199] of JSC *"AST"* shows presence of biogas and slightly solar. Anyway, the volumes are gradually growing, however, in obedience to the "National Energy and Climate Plan for 2021–2030", Latvia does not plan to increase biomass and biogas capacity for electricity generation. Lithuanian other RES consist mostly of solar, biomass and other. In researched time period, installed capacity of Lithuanian other RES was fluctuating, but saved the leading position between Baltic courtiers, however, situation changed in 2019, when in Estonia rapidly increased installed solar energy capacity. So, Estonian other RES are solar, biomass and waste.

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[197] The Ministry of Economics of the Republic of Latvia. National Energy and Climate Change Plan 2021–2030. URL: [Accessed 25.09.2020]

[198] *Nord Pool* vēsturiskie dati: http://nordpoolspot.com/historical-market-data/.

[199] JSC Augstsprieguma tīkls. Latvian electricity market overview. URL: http://www.ast.lv/en/electricity-market-review?year=2017&month=10 [Accessed 05.08.2020]

There are four main groups of factors that affect introduction of wind energy technologies in Latvia (excluding availability of financial resources for investment):

- regulatory environment,
- political environment,
- population attitude, and
- accessibility of the territory.

In each of the four groups have many facets that can either facilitate or damage wind energy.

So, in recent years, EOLUS, a wind energy developer of Swedish origin, has been working on a new wind farm project in Dobele and Tukums counties with planned investments of more than 200 million and the installation of at least 35 wind turbines with a total capacity of more than 100 MW. The company prepared and submitted an environmental impact assessment report in 2018[200] and in July 2019, the State Environmental Service for the project gave the green light[201]. However, complaints from local communities show that the main problems are noise, infrasound, ultrasound and vibration, and claim that they adversely affect human health and quality of life within 20 kilometres of a wind farm[202]. However, the developer has not yet implemented the project, although according to unofficial information, the idea of implementing the project is not rejected.

To this end, it is worth to mention that Baltic countries are using their geographical, nature potential, implementing rational maintenance and are working on modernization and reconstruction for a sustainable future of energy system. The capacities of wind and solar installations are growing in not only Baltics, but also all-around Europe. The Baltic countries have not used all the potential, which in combination with the EU target of carbon neutral by 2050, investments, support schemes and auctions, smart strategy and implementation can lead us to sharply increasing RES, especially of wind and solar capacities. According to Latvia's National Energy and Climate Plan 2021–2030, the Latvian electricity transmission system is capable of accepting up to 800 MW of additional capacity from new RE plants, which is about a third of all electrical capacities currently installed in Latvia.

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[200] Estonian, Latvian & Lithuanian Environment Ltd., Vēja elektrostaciju parku Dobele un Pienava būvniecība Dobeles un Tukuma novados. Ietekmes uz vidi novērtējuma ziņojuma kopsavilkums (2018).

[201] EOLUS Vind AB. 19.07.2019. EOLUS receives environmental approval for up to 35 wind turbines in Latvia, https://www.eolusvind.com/news/eolus-receives-environmental-approval-for-up-to35-windturbines-in-latvia/?lang=en

[202] NRA. 18.09.2018. Iedzīvotāji vāc parakstus pret vēja parka izbūvi Dobeles un Tukuma novados, https://nra.lv/latvija/regionos/257820-iedzivotaji-vac-parakstus-pret-veja-parkaizbuvidobeles-un-tukuma-novados.htm

Conclusions

1. The chapter represents the assessment conducted by the author of various legal documents and regulations suggested by international organisations such as UN, EU as well as the Cabinet of Ministries of the Republic of Latvia. The more liberalized the market, the more it responds to fluctuations in demand and supply. In an effort to maximize the liberalization of the European energy market, European market decision makers intended to use it as a tool that would provide an ever-increasing, growing and diversified range of offers, which would put downward pressure on prices.
2. To this end, the Baltic countries have not used all the potential, which in combination with the EU target of carbon neutral by 2050, investments, support schemes and auctions, smart strategy and implementation can lead us to sharply increasing RES, especially of wind and solar capacities. According to Latvia's National Energy and Climate Plan 2021–2030, the Latvian electricity transmission system is capable of accepting up to 800 MW of additional capacity from new RE plants, which is about a third of all electrical capacities currently installed in Latvia.
3. As have been mentioned before, the correlation with the wholesale price of electricity in the Nord Pool Latvian trade area with of generated wind energy is considered weak. However, for hours with the highest price situation could be considerably different.

To estimate the impact of consumption changes on the day-ahead electricity price, the author in Chapter III analyses the relationships between the fundamental factors and electricity prices in Latvia, the availability of renewable resources such as hydro and wind should have statistically significant influence on day-ahead prices in Latvia because short-term marginal costs of hydro and wind stations are negligible.

3 Trends of Indicators in Electricity Sector and Factors Influencing Wholesale Electricity Price in Latvia

The represented investigation in relation to the analysis of industry statistical indicators of electricity production and imports in the time period 2014–2019, average hourly electricity consumption and the price of one MWh of wind power in 2019, and similar indicators for hours of peak consumption in Latvia allowed determining the possibility of implementation of the suggested business model for demand response mechanism. Calculated characteristics and trends of indicators of export, import, and total exchange turnover and electricity consumption in Latvia to estimate it potential.

Calculation of trends of indicators, approximating formulae dependencies and the coefficients of determination for the relevant diagrams and charts are based on big data collected from the Latvian transmission system operator (Augstsprieguma tīkls), Central Statistical Bureau of Latvia, and Nord Pool the power exchange. The data used in the empirical study is collected from hourly data from the period 1 January 2014 to 31 December 2019.

The price in the wholesale market Nord Pool indicates the system need for flexibility. Simply put, flexibility in the electricity market can be understood as the ability to react to market signals by increasing or decreasing production and consumption in response to situations of abundance or scarcity. Flexibility is coordinated by prices: high prices signal scarcity, encouraging producers to ramp up generation and consumers to curtail load. Low prices, in turn, indicate abundance, nudging producers to slow generation and consumers to expand demand.[203] As a result, the more flexibility there is in both supply and demand, the more they act to minimise price variation and the more stable the prices will be. Therefore, price variation is a simple way of measuring flexibility in the electricity market, abstracting it from its more complex technical aspects.[204] Thus, the relationship between the electricity price and the wind power generation in an electricity power market is investigated in this chapter. The spot price, the down regulation price and the up-regulation price generally decreases when the wind power penetration in the power system increases[205]. The statistical characteristics of the spot price for different wind power penetration are analysed.

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[203] Skytte, K., Bergaentzlé, C., Fausto, F.J., Gunkel, P.A. 2019. Flexible Nordic Energy Systems. Summary Report, 120, Nordic Energy Research, https://www.nordicenergy.org/article/act-fast-and-nordic-while-paving-the-way-for-carbon-neutrality/ ISBN: 978-87-93458-65-9[Accessed 28.07.2019].

[204] Ibid.

[205] Hu, W., Chen Z. and Bak-Jensen, B. 2010. The Relationship Between Electricity Price and Wind Power Generation in Danish Electricity Markets, Asia-Pacific Power and Energy Engineering Conference, Chengdu, China, 1-4, doi: 10.1109/APPEEC.2010.5448739. [Accessed 28.07.2019].

An important aspect of aggregator implementation is to conduct more in-depth analysis and identify how consumers respond to electricity prices (will be addressed in Chapter 3).

Several approaches have been proposed to address demand-supply variability in deregulated electricity sector. The approaches include Storage, Demand Side Management (DSM), Auctions and Market Power Mitigation.[206] In electricity markets, the structure of the supply side is commonly represented by the merit order curve. It represents the marginal generation costs of all conventional power plants, using fossil fuel – common power plant types and fuels are hydro power, nuclear, *lignite*, coal, gas and oil. The shape of the curve mainly depends on the technologies being used for power generation and their respective fuel prices. However, variable renewable energy generation is becoming more and more important to the overall market in recent years. Wind power has greatly increased its share in the electricity generation mix during the past decade and it represents the variable renewable energy source with the highest total installed capacity around the world.[207] Since renewable energy technologies do not rely on fossil fuel inputs to generate electricity, their fuel costs are close to be zero. What is unique about the generation from variable renewable energies is its stochastic nature that is driven by wind speeds and solar radiation.

Due to the fact that the electricity price is determined by demand and supply and therefore endogenously specified within the market, hourly expected wind generation have been used as a variable to proxy electricity prices.[208]

This research will allow revealing the relevance of the research topic of economic environment for DR aggregator, considering integration of the wind power.

3.1 Methodology for analysis of relationships between physical parameters and real-time price variables applicable to the demand response mechanism

The goal of this analysis is whether there is a connection of the electricity price and the wind power generation, and physical indicators of energy sector of Latvia, and if there is such connection, whether this fact influence on the demand perspective and on the relevance of the examined topic.

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[206] Nooriya A.M., Albadi, M.H. 2020. Demand response in electricity generation planning, The Electricity Journal, Volume 33, Issue 7, 106799, ISSN 1040-6190, https://doi.org/10.1016/j.tej.2020.106799. [Accessed 28.07.2019]. (https://www.sciencedirect.com/science/article/pii/S1040619020300919) (viewed on 14.10.2020)

[207] Brancucci Martinez-Anido, Carlo, Greg Brinkman, and Bri-Mathias Hodge. 2016. The Impact of Wind Power on Electricity Prices. Renewable Energy 94 (August): 474–87. https://doi.org/10.1016/j.renene.2016.03.053. [Accessed 20.09.2019].

[208] Knaut, A., Paulus, S. 2016. Hourly price elasticity pattern of electricity demand in the German day-ahead market, EWI Working Paper, No. 16/07, Institute of Energy Economics at the University of Cologne (EWI), Köln. [Accessed 20.09.2019].

For carrying out this analysis, the quantitative analysis of the results of research has been chosen by the author.

The distribution of the data of research variables is no different from the normal distribution. Therefore, for the further research of empirical data were used the methods of parametric statistics – the coefficients of linear correlation of Pearson for the research of the connection.

In this chapter author proposes a methodology for the complex analysis of correlation and regression dependences of the relationship between the electricity price and the wind power generation in an electricity market of Latvia, based on the adaptation of the corresponding classical mathematical models. The methodology is based on the adaptation of correlation and regression classical models' analysis in relation to the analysis of industry statistical indicators of electricity production and imports in the period 2014–2019 (See Chapter 1), average hourly electricity consumption and the price of one MWh of wind power in 2019, and similar indicators for hours of peak consumption from 8:00 to 12:00. Because the electricity price is determined by demand and supply and therefore endogenously specified within the market, hourly expected wind generation have been used as a variable to proxy electricity prices. The statistical indicators are supplemented with details of electricity consumption and wind power generation unit price on average per day and at peak hours (from 8:00 to 12:00) monthly in 2019. The author has also substantiated the use of the sinusoidal dependence of wind energy indicators on the month of the year, as a basic model, for the correlation study. It is shown that if the maximum and minimum outliers of the studied data do not have the same average deviations from the general average level, then it is necessary to introduce additional accompanying variables that identify these outliers, which leads to the corresponding modified model. There are established the regression dependences of monthly wind power data. There also presented the calculated data on the validation of the obtained models. Calculations were made using the algorithmic language *MATHCAD*. The developed models are recommended as an analytical tool for the real time indicators for understanding and estimation of demand response mechanism business model of electricity aggregator.

One of the main tasks of the chapter is to develop a methodology for a comprehensive analysis of correlation and regression dependencies of an electricity sector physical and price indicators, based on the adaptation of the corresponding classical mathematical models. Author believe that the proposed adapted models can be used in the understanding of the peculiarities of the DR mechanism and development process of the Latvian regional aggregator.

The underlying regression model – Classical analyzing model

In general, regression allows us to approximate a mathematical relationship between two or more variables if their values are known in a number of points. For analysis purposes, the processed statistical data is usually presented in the form of table 3.1, where *V1* and *V2* are interrelated indicators related to the same object of research and calculated in increasing time intervals (i). For the electricity sector, *V1* means physical indicators expressed in MWh and *V2* are price indicators in EUR / MWh.

Table 3.1

General presentation of statistical data for a complex analysis of natural and price indicators of the electricity sector

Vector of indicator / serial number	**1**	**2**	**i**	***n***
$V1$	$V1_1$	$V1_2$	$V1_i$	$V1_n$
$V2$	$V2_1$	$V2_2$	$V2_i$	$V2_n$

Source: created by the author based on[209] data

In the following formulas the available statistical data are presented in the form of the corresponding matrices *Tj*. Average value, dispersion and standard deviation for the data represented by the vector *V* (*V* takes the value *V1* or *V2*) of matrix *Tj* are calculated using the usual equations[210] (see Eq. 3.1):

$$E(V) = \frac{1}{n}\sum_{i=1}^{n} V_i \tag{3.1}$$

$$D(V) = \frac{1}{n-1}\sum_{i=1}^{n}\left(V_i - E(V)\right)^2 \tag{3.2}$$

$$\sigma(V) = \sqrt{D(V)} \tag{3.3}$$

The covariance of two variables, presented in the Table 3.1, is calculated by the equation[211] (see Chapter 13):

$$cov(V1, V2) = \frac{1}{n}\sum_{i=1}^{n} V1_i V2_i - E(V1)E(V2) \tag{3.4}$$

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[209] Seber, G.A.F. 1977. Linear regression analysis. John Wiley and Sons, New York – London – Sydney – Toronto.

[210] Afifi, A.A., Azen S. 1979. Statistical Analysis. A Computer Oriented Approach. Academic Press, New York – San Francisco – London.

[211] Adams, A., Bloomfield, D., Booth, Ph., England, P. 1993. Investment Mathematics and Statistics. Graham @ Trotman, London – Dordrecht – London.

The correlation coefficient is defined as follows:

$$corr(V1, V2) = \frac{cov(V1,V2)}{\sigma(V1)\sigma(V2)} \tag{3.5}$$

The general polynomial regression model[212] assumes the dependence of the random variable *Yi* from the values of the factors (related variables, regressors) $x_{\mathrm{i},1}$, $x_{\mathrm{i},2}$, ..., $x_{\mathrm{i,k}}$ in the *i*-th observation:

$$,Y_i = \beta_0 + \beta_1 x_{\mathrm{i},1} + \cdots + \beta_k x_{i,k} + Z_i, i = 1, \dots, n \tag{3.6}$$

$\beta_1, \dots, \beta_k$ – regression coefficients

Z_i – random component with a zero average value and final standard deviation

n – number of observations.

The regression task is to estimate the coefficients $\beta_0, \beta_1, \dots, \beta_k$ based on *n* observations. In the *i*-th observation, the values of the related variables $x_{i,1}$, $x_{i,2}, \dots, x_{i,k}$ and the value of the random variable Y_i are fixed.

The estimate of the regression coefficients $\beta_0, \beta_1, \dots, \beta_k$ is presented in vector-matrix form. In regard to this, the following vectors and matrices are considered:

$Y = (Y_1, \dots, Y_n)^T$ – a column vector of dependent variables (*T* means matrix transposition);

$X = (x_{i,j})$ – matrix of related variables of size *n*×(*k*+1), whose lines correspond to the observations, but columns to the regression coefficient;

$\beta = (\beta_0 , \dots, \beta_k)^{\mathrm{T}}$ – column vector.

The classical estimate of the regression coefficients is calculated by the equation[213]:

$$\hat{\beta} = (X^T X)^{-1} X^T Y \tag{3.7}$$

$(X^T X)^{-1}$ means the matrix inverse to $X^T X$.

In this case, the estimate of the random variable Y_i is:

$$\hat{Y}_i = \ddot{\beta}_0 + \widehat{\beta_1} x_{\mathrm{i},1} + \cdots + \hat{\beta}_k x_{i,k}, i = 1, \dots, n \tag{3.8}$$

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[212] Seber, G.A.F. 1977. Linear regression analysis. John Wiley and Sons, New York – London – Sydney – Toronto, Ch.3.

[213] Seber, G.A.F. 1977. Linear regression analysis. John Wiley and Sons, New York – London – Sydney – Toronto.

Adaptation of Classical Mathematical Models for the Analysis of Correlation and Regression Dependences of Natural and Price Indicators of the Electricity Sector

To start with, there have been developed mathematical models for the analysis of the electricity sector natural and price indicators in relation to the processing of statistical data presented by tables with specific natural and price indicators of:

- electricity production and imports in the time period 2014–2019 (Table 3.2);
- average hourly electricity consumption and the price of one MWh of wind power in 2019 (Table 3.3), and
- similar indicators for hours of peak consumption from 8:00 to 12:00 CET / GTM+2 (Table 3.4).

Motivation of choosing variables for Table 3.3 and table 3.4 is as follows. As mentioned in chapter 1, implementation of DR programs can result in shift peak demand, enhance system reliability, can reduce transmission bottleneck and highly priced energy bills by shifting or re-adjusting consumption patterns. It can also reduce the effects of intermittent RE generation since the capacity of introduced RE sources will be optimally minimal, and the consumer can also be encouraged to embark on self RE generation and sell self-produced excess energy to the grid. Calculation of trends of indicators, approximating formulae dependencies and the coefficients of determination for the relevant diagrams and charts are based on big data collected from the Latvian transmission system operator, Central Statistical Bureau of Latvia, and the Nord Pool power exchange. The data used in the empirical study is collected from hourly data from the period 1 January 2014 to 31 December 2019. (See Annex 1). All the calculations in this and subsequent sections were carried out by using the *Mathcad* programming language.

Table 3.2

Latvian electricity sector net electricity production and import, MWh, 2014–2019

Indicator, MWh	2014	2015	2016	2017	2018	2019
Net electricity production [214]	4857	5384	6228	4401	6500	6108
Import	5338	5247	4827	4074	5172	4612

Source: created by the author based on statistical table ENG090 data

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[214] The data for Latvia is extracted from statistical table ENG090.

Table 3.3

Average hourly calculated natural and price indicators of wind energy in Latvia, 2019

Indicator	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average hourly wind power generation (MWh)	171	219	222	141	135	89	122	58	161	159	183	224
Average wind power price (EUR / MWh)[215]	56	47	40	44	44	45	49	39	49	47	45	39

Source: created by the author based on statistical table ENG090 data

Table 3.4

Average hourly calculated natural and price indicators of wind energy during the peak hours (from 8:00 to 12:00 CET / GTM+2) in Latvia, 2019

Indicator	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average hourly peak wind power generation (MWh)	174	211	230	118	123	76	96	47	149	153	181	213
Average peak wind power price (EUR / MWh)	64	50	43	52	57	66	61	60	67	56	48	42

Source: created by the author based on statistical table ENG090 data[216]

The calculated average per diem and peak hours indicators of wind energy are equal to 157 and 147.6 MWh, 45.3 and 55.5 EUR / MWh accordingly Tables 3.3 and 3.4. Indicators differ insignificantly in volume (6 %) and significantly, in price (18 %), moreover, during peak hours, the average consumption of wind power is less, but the average hourly price is higher.

As the next step, author has developed a regression model that describes the dependence of the indicators in Table 3.3 and 3.4 from month number *i*. The number of observations is the number of months, i.e. n = 12.

The related variables should be chosen so that the smoothing of the presented data is acceptable. The smoothing criterion is the sum of the squares of the deviations:

$$R = \sum_{i=1}^{12} \left(Y_i - \hat{Y}_i\right)^2 \tag{3.9}$$

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[215] Price data extracted from the corresponding Elspot Prices annual files with hourly resolution.

[216] European Network of Transmission System Operators for Electricity. URL: https://www.entsoe.eu [Accessed 25.09.2020]

Initially, it was supposed to use a general polynomial regression model (3.8)[217]:

$$Y_i = \beta_0 + \beta_1 i^2 + \beta_1 i + \cdots + \beta_k i^k + Z_i, i = 1, \dots, 12.$$

However, the results were completely unsatisfactory. This is explained in the monograph[218]: “It is well known that the matrix $X^T X$ is quite poorly conditioned”. Moving further the author points out: “One of the ways to reduce the influence of bad conditionality of the matrix $X^T X$ is to use Chebyshev polynomials …”. This possibility was tested, but the result was again unsatisfactory. The author adopted for further research the sinusoidal dependence of the indicator on the month number:

$$Y_i = \beta_0 + \beta_1 \sin\left(\frac{i-c}{6}\pi\right) + Z_i, i = 1, \dots, 12 \tag{3.10}$$

c – known integer with possible values from 0 to 11.

In this case, there is a single related variable $x_{i,1} = \sin\left(\frac{i-c}{6}\pi\right)$. Statistics are given by the vector $Y = (Y_1, Y_2, \dots, Y_{12})$ and the smoothing criterion is written as:

$$R = \sum_{i=1}^{12}\left(Y_i - \hat{Y}_i\right)^2 = \sum_{j=1}^{12}\left(\hat{\beta}_0 + \widehat{\beta_1}\sin\left(\frac{j-c}{6}\pi\right) - Y_i\right)^2 \tag{3.11}$$

It allows you to get simple estimation equations:

$$\beta_0 = \frac{1}{12}\sum_{i=1}^{12} Y_j \tag{3.12}$$

$$\beta_1 = \left(\sum_{i=1}^{12}\sin\left(\frac{i-c}{6}\pi\right)(Y_i - \beta_0)\right) * \frac{1}{\sum_{i=1}^{12}\left(\sin\left(\frac{i-c}{6}\pi\right)\right)^2}$$

The latter formula follows from the fact that the derivative to $\beta_1$from R gives the following relation:

$$\beta_0 \sum_{i=1}^{12}\sin\left(\frac{i-c}{6}\pi\right) + \beta_1 \sum_{i=1}^{12}\left(\sin\left(\frac{i-c}{6}\pi\right)\right)^2 - \sum_{i=1}^{12} Y_i \sin\left(\frac{i-c}{6}\pi\right) = 0$$

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[217] Afifi, A.A., Azen S. 1979. Statistical Analysis. A Computer Oriented Approach. Academic Press, New York – San Francisco – London.

[218] Adams, A., Bloomfield, D., Booth, Ph., England P. 1993. Investment Mathematics and Statistics. Graham @ Trotman, London – Dordrecht – London, 209.

It remains only to emphasize that the constant c is chosen so that the criterion R is minimal. Application of the obtained estimates shows that individual outliers violate smoothing. The estimates can be improved by introducing an additional related variable of +1 for the cases with the highest values and -1 for the cases with the lowest values[219]. According to Tables 3.3 and 3.4 the highest values of average hourly wind power generation and average hourly peak wind power generation are in February, March and December, but the lowest values are in June and August. If using Boolean variables

$$x_{i,2} = \begin{bmatrix} -1, \text{if } i = 6 \text{ or } 8, \\ 1, \text{if } i = 2, 3 \text{ or } 12, \\ 0, \text{otherwise} \end{bmatrix} \tag{3.13}$$

where i – number of month, then the modified regression model can be written as follows:

$$Y_i = \beta_0 + \beta_1 \sin\left(\frac{i-c}{6}\pi\right) + \beta_2 x_{i,2} + Z_i, i = 1, \dots, 12 \tag{3.14}$$

Model (3.14) assumes that the maximum and minimum outliers have the same average deviations from the total average. If this is not the case, then additional related variables should be introduced to identify the maximum and minimum outliers:

$$x_{i,2} = \begin{bmatrix} -1, \text{if } i = 6 \text{ or } 8, \\ 0, \text{otherwise} \end{bmatrix} \tag{3.15}$$

$$x_{i,3} = \begin{bmatrix} 1, \text{if } i = 2, 3 \text{ or } 12, \\ 0, \text{otherwise} \end{bmatrix} \tag{3.16}$$

The regression model will now look like this:

$$Y_i = \beta_0 + \beta_1 \sin\left(\frac{i-c}{6}\pi\right) + \beta_2 x_{i,2} + \beta_3 x_{i,3} + Z_i, i = 1, \dots, 12 \tag{3.17}$$

Next, the author considers a regression model that approximates both tables, Table 3.3 and 3.4, at once. To do this, the author introduces an additional related variable identifying the table under consideration, and the estimation will be carried out on all data from both Tables

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[219] Adams, A., Bloomfield, D., Booth, Ph., England, P. 1993. Investment Mathematics and Statistics. Graham @ Trotman, London – Dordrecht – London.

3.3 and 3.4. Let us illustrate this using the example of the last model (3.17). A related variable $x_{i,4}$ will be added here:

$$x_{i,4} = \begin{bmatrix} 1, \text{if the observation refers to table 1,} \\ 0, \text{otherwise} \end{bmatrix} \tag{3.18}$$

As a result, we get the model:

$$Y_i = \beta_0 + \beta_1 \sin\left(\frac{i-c}{6}\pi\right) + \beta_2 x_{i,2} + \beta_3 x_{i,3} + \beta_4 x_{i,4} + Z_i, i = 1, \dots, 12 \tag{3.19}$$

a. The Results of Table 2.2 – Net electricity production and Import data estimation

Table 3.5[220] contains calculations of average indicators (3.1–3.3), dispersion and standard deviations, according to the data in Table 3.2

Table 3.5

The calculated values of the indicators (1 – 3) according to the Table 2

	Net electricity production	Import
Average, *E*	5413×10^3	4.878×10^3
Dispersion, *D*	4.978×10^5	2.308×10^5
Standard deviation, σ	705.541	480.41

Source: created by the author

The covariance calculated by formulas (3.4) and (3.5) for the net electricity production and import is 5.772×10^4, and the correlation coefficient is 0.17. We see that these indicators Net electricity production and Import of electricity are positively correlated, but the degree of correlation is low.

b. The Results of Processing Monthly Fluctuations of the Indicators in Tables 3.3 and 2.4

The calculated indicators of natural and price statistics – Average hourly wind power and Average hourly price from Tables 3.3, and Average hourly peak wind power and Average hourly peak prices from Table 3.4 are given in Table 3.6. The covariance for the two presented indicators is 5.25 for Table 3.3 and -308 for Table 3.4. The corresponding correlation coefficients are 0.021 and -0.626. It can be stated, that the statistical characteristics of these two tables are mostly different.

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[220] In this and subsequent tables all sources: created by the author.

Table 3.6

The calculated values of the indicators (3.1–3.3) according to the Tables 3.3 and 3.4

	Average hourly wind power production (MWh)		**Average price (EUR)**	
	Table 2	**Table 3**	**Table 2**	**Table 3**
Average, *E*	157	147.583	45.583	55.5
Dispersion, *D*	2.713×10^3	3.302×10^3	23.5154	73.182
Standard deviation, *σ*	52.084	57.462	4.849	8.555

Source: created by the author

Now it is time to present the results of the analysis of monthly fluctuations in the statistical data of Tables 3.3 and 3.4, where the regression coefficients β_0 and β_1 are estimated for different values of the constant *c*, and the criterion smoothing (3.11) is calculated to “remove noise” from a data set, allowing important patterns to stand out. Tables 3.7 and 3.8 show the obtained results. It should be highlighted that the best results are in that case, when the value of the constant *c* is equal to 4. This value will be used in the next calculations.

Table 3.7

The values of criterion (3.11) at different *c* for the indicators of Table 3.3

c	0	1	2	3	4	5	6	7	8	9	10	11
R_1	155	173	157.37	118.23	90.88	115.44	155.29	172.72	157.37	118.23	90.88	115.14
R_2	16	16	15.869	15.868	15.967	16.067	16.069	15.97	15.869	15.868	15.967	16.067

Source: created by the author

Table 3.8

The values of criterion (3.11) at different *c* for the indicators of Table 3.4

c	0	1	2	3	4	5	6	7	8	9	10	11
R_1	171.67	190.58	171.13	124.11	92.48	124.85	171.64	190.58	171.13	124.11	92.48	124.85
R_2	25.57	28.08	27.89	25.14	22.31	22.55	25.57	28.08	27.89	25.14	22.31	22.55

Source: created by the author

For the model (3.10) with $c = 4$, the coefficients calculated by formulas (3.11) and (3.12) were as follows- Table 3.3: for the first indicator $\beta_0 = 157$ and $\beta_1 = -59.974$; for the second indicator $\beta_0 = 45.333$ and $\beta_1 = -0.789$. Table 3.4: for the first indicator $\beta_0 = 147.583$ and $\beta_1 = -68.029$; for the second indicator $\beta_0 = 55.5$ and $\beta_1 =7.157$. Comparison of actual and smoothed data is given in Tables 3.9 and 3.10.

Table 3.9

Actual and smoothed monthly data for the indicators of Table 3.3

i	1	2	3	4	5	6	7	8	9	10	11	12
Y_1	171	219	222	141	135	89	122	58	161	159	183	224
$\hat{Y}_i$	216.9	208.9	187.0	157.0	127.0	105.1	97.0	105.1	127.0	177.0	187.0	209.0
Y_2	56	47	40	44	44	45	49	39	49	47	45	39
$\hat{Y}_2$	46.12	46.02	45.73	45.33	44.94	44.65	44.55	44.65	44.94	45.33	45.73	46.02

Source: created by the author

Table 3.10

Actual and smoothed monthly data for the indicators of Table 3.4

i	1	2	3	4	5	6	7	8	9	10	11	12
Y_1	174	211	230	118	123	76	96	47	149	153	181	213
$\hat{Y}_i$	215.6	206.5	181.6	147.6	113.6	88.7	79.6	88.7	113.6	147.6	181.6	206.5
Y_2	64	50	43	52	57	66	61	60	67	56	48	42
$\hat{Y}_2$	48.3	49.3	51.9	55.5	59.1	61.7	62.7	61.7	59.1	55.5	51.9	49.3

Source: created by the author

The next step is a repeat of the calculations for the case of introducing an additional related variable (3.13). (See model (3.14)) The data presented in Tables 3.11 and 3.12 indicate that the best values of the constant c are: $c = 2$ for the first indicator of Table 3.3 and $c = 3$ in other cases.

Table 3.11

Values of criterion (3.11) for model (3.14) at different *c* for indicators of Table 3.3

c	0	1	2	3	4	5	6	7	8	9	10	11
R_1	52.65	45.75	38.30	40.58	54.88	57.29	52.65	45.75	38.30	40.58	54.88	57.29
R_2	15.92	15.72	15.47	15.39	15.81	16.01	15.92	15.72	15.47	15.39	15.81	16.01

Source: created by the author

Table 3.12

Values of criterion (3.11) for model (3.14) at different *c* for indicators of Table 3.4

c	0	1	2	3	4	5	6	7	8	9	10	11
R_1	74.86	65.72	54.30	54.06	74.40	79.98	74.86	65.72	54.30	54.06	74.40	79.98
R_2	19.10	19.10	19.02	18.83	18.83	19.00	19.10	19.10	19.02	18.83	18.83	19.00

Source: created by the author

For model (3.14) with the chosen values *c* the coefficients calculated by formula (3.7) are as follows- Table 3.3: for the first indicator β_0 = 151.2, β_1 = -14.77 and β_2 = 69.72, for the second indicator β_0 = 45.49, β_1 = -2.03 and β_2 = -1.92. Table 3.4: for the first indicator β_0 = 142.55, β_1 = -28.86 and β_2 = 60.37, for the second indicator β_0 = 56.24, β_1 = 0.92 and β_2 = -8.90. Comparison of actual and smoothed data is given in Tables 3.13 and 3.14.

Table 3.13

Actual and smoothed monthly data for model (3.14) and indicators of Table 3.3

i	1	2	3	4	5	6	7	8	9	10	11	12
Y_1	171	219	222	141	135	89	122	58	161	159	183	224
$\hat{Y}_i$	158.57	220.91	213.53	138.40	136.42	68.68	143.81	81.47	158.57	163.98	165.96	233.7
Y_2	56	47	40	44	44	45	49	39	49	47	45	39
$\hat{Y}_2$	47.25	44.59	43.58	44.48	43.74	45.38	43.74	46.39	45.93	46.51	47.25	45.61

Source: created by the author

Table 3.14

Actual and smoothed monthly data for model (3.14) and indicators of Table 3.4

i	1	2	3	4	5	6	7	8	9	10	11	12
Y_1	174	211	230	118	123	76	96	47	149	153	181	213
$\hat{Y}_i$	167.55	217.36	202.93	128.22	117.56	53.32	117.56	67.75	142.55	156.98	167.55	231.79
Y_2	64	50	43	52	57	66	61	60	67	56	48	42
$\hat{Y}_2$	55.45	46.88	47.34	56.70	57.04	66.06	57.04	65.60	56.24	55.78	55.45	46.23

Source: created by the author

The next step is a repeat of the calculations for the case of introducing two additional related variables (3.15) and (3.16), identifying the maximum and minimum outliers. (See model (3.17)) As with the previous case, the data presented in Tables 3.15 and 3.16 indicate that the best values of the constant *c* are: *c =2* for the first indicator of Table 3.2 and *c = 3* – in other cases.

Table 3.15

Values of criterion (3.11) for model (3.17) at different *c* for indicators of Table 3.2

c	0	1	2	3	4	5	6	7	8	9	10	11
R_1	52.41	45.59	38.00	39.37	53.54	56.70	52.41	45.59	38.00	39.37	53.54	56.70
R_2	12.78	12.69	12.39	11.95	12.16	12.63	12.78	12.69	12.39	11.95	12.16	12.63

Source: created by the author

Table 3.16

Values of criterion (3.11) for model (3.17) at different *c* for indicators of Table 3.3

c	0	1	2	3	4	5	6	7	8	9	10	11
R_1	74.84	65.62	54.25	53.88	73.76	79.93	74.84	65.62	54.25	53.88	73.76	79.93
R_2	17.96	17.90	17.78	17.68	17.81	17.95	17.96	17.90	17.78	17.68	17.81	17.95

Source: created by the author

For model (3.17) with the chosen values *c* the coefficients calculated by formula (3.7) are as follows- Table 3.2: for the first indicator β_0 = 152.1, β_1 = -14.51, β_2 = -72.32 and β_3 = 67.92, for the second indicator β_0 = 57.86, β_1 = 1.26, β_2 = 4.20 and β_3 = -12.23. Table 3.3: for the first indicator β_0 = 142.0, β_1 = -28.98, β_2 = -58.77 and β_3 = 61.51, for the second indicator β_0 = 47.71, β_1 = -1.56, β_2 = -4.55 and β_3 = -6.49. Comparison of actual and smoothed data is given in Tables 3.17 and 3.18.

Table 3.17

Actual and smoothed monthly data for model (3.17) and indicators of Table 3.2

i	1	2	3	4	5	6	7	8	9	10	11	12
Y_1	171	219	222	141	135	89	122	58	161	159	183	224
$\widehat{Y}_i$	159.36	219.90	212.64	139.54	137.60	67.22	144.85	79.78	159.36	164.67	166.62	232.46
Y_2	56	47	40	44	44	45	49	39	49	47	45	39
$\widehat{Y}_2$	49.01	42.00	41.22	46.94	46.36	41.61	46.36	42.39	47.71	48.49	49.06	42.78

Source: created by the author

Table 3.18

Actual and smoothed monthly data for model (3.17) and indicators of Table 3.3

i	1	2	3	4	5	6	7	8	9	10	11	12
Y_1	174	211	230	118	123	76	96	47	149	153	181	213
$\widehat{Y}_i$	167.10	218.00	203.51	127.51	116.91	54.26	116.90	68.74	142.00	156.49	167.10	232.45
Y_2	64	50	43	52	57	66	61	60	67	56	48	42
$\widehat{Y}_2$	56.77	45.00	45.63	58.49	58.95	63.31	58.95	62.68	57.86	57.23	56.77	44.37

Source: created by the author

As the tables show, the developed model of the regression quite precisely describes our data. R-square is much closer to the unit that means that the model is qualitative. In addition, the lack of residual autocorrelation indicates us to the quality of the forecast.

Comparison of the two models (3.14) and (3.17) for the purpose of their practical use leads to the following recommendations. If we proceed from the formal criterion, the sum of squares of deviations (3.9), then the preference should be given to the model (3.17). However, expert analysis shows that the results provided by the model (3.14) are more logically justified. In this regard, model (3.14) is recommended for practical use.

c. The Results of Regression Analysis of the Indicators in Tables 3.3 and 3.4

At the end of the analysis, we will establish the regression dependences of the indicators presented in Tables 3.3 and 3.4. These indicators are the average hourly wind power (MWh) production during peak hours and the average price of wind power (EUR / MWh). We will denote the monthly values of these variables X_i and Y_i.

Let us determine the dependence of the average price of wind energy Y_i from the average hourly wind energy (EUR / MWh) during peak hours X_i in a given month. A one-dimensional version of general regression will be considered (3.6):

$$Y_i = \beta_0 + \beta_1 x_i + Z_i, i = 1, \ldots, 12 \tag{3.20}$$

Z_i – is a random component Z_i with zero mean.

Classical evaluation of unknown parameters (for example, [221] p. 178) can be written explicitly, without using vector-matrix notation:

$$\hat{\beta}_1 = \frac{1}{\sum_{i=1}^{12}(x_i - \bar{x})^2} \sum_{i=1}^{12} Y_i\,(x_i - \bar{x}) \tag{3.21}$$

$$\hat{\beta}_0 = \bar{Y} - \hat{\beta}_1 \bar{x},$$

where

$$\bar{x} = \frac{1}{12}\sum_{i=1}^{12} x_i\,, \bar{Y} = \frac{1}{12}\sum_{i=1}^{12} Y_i.$$

The author presents the results of calculations using these formulas and using the data from Table. 3.4, because for Table 3.3, the correlation coefficient for the considered indicators is positive, which does not correspond to already known regularity. The estimates of the regression coefficients are as follows: $\hat{\beta}_0 = 70.476, \hat{\beta}_1 = -0.102$. Therefore, the regression dependence has the form:

$$\hat{Y}_i = 70.476 - 0.102 x_i, i = 1, \ldots, 12 \tag{3.22}$$

The table below shows the values calculated by formula (3.22) and the corresponding actual data from Table 3.4.

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[221] Seber, G.A.F. 1977. Linear regression analysis. John Wiley and Sons, New York – London – Sydney – Toronto.

Table 3.19

Actual and smoothed monthly data for the second indicator of Table 3.4

i	1	2	3	4	5	6	7	8	9	10	11	12
Y_i	64	50	43	52	57	66	61	60	67	56	48	42
$\hat{Y}_i$	52.75	48.97	47.04	58.46	57.95	62.74	60.70	65.70	55.30	54.89	52.03	48.77

Source: created by the author

Conclusions

The author has substantiated the use of the sinusoidal dependence of wind energy indicators on the month of the year, as a basic model, for the correlation study. It is shown that if the maximum and minimum outliers of the studied data do not have the same average deviations from the general average level, then it is necessary to introduce additional accompanying variables that identify these outliers, which leads to the corresponding modified model. There are established the regression dependences of monthly wind power data. There also presented the calculated data on the validation of the obtained models.

1. In developing process of a methodology for statistical analysis of wind energy yearly and monthly (2019) data, it was established that for practical use should be applied analysis methods that give not only good quality criteria, but also the values of the considered indicators corresponding to the logical meaning. Polynomial regression has proven to be an ineffective tool for electricity demand forecasting. One of its main strengths is the negligible computational time it takes to perform forecasts without losing much in terms of accuracy. Furthermore, the forecasting model can be improved by certain modifications, the most promising of which has turned out to be subtraction of the model residuals averaged over hour-of-day.
2. Multiple (polynomial) regression has proven to be an ineffective tool for the analysis of monthly statistical data gave unsatisfactory results, therefore, it is recommended to use the model of sinusoidal dependence of the corresponding indicators on the month number.
3. While other modifications (*x* component and time series filtration) did not produce a consistently beneficial effect over the whole dataset, there were days when their inclusion aided in improving the accuracy. Thus, a model, which automatically selects the features the forecasting program, should consider before each daily forecast is advisable. Additionally, it should consider automatic selection of the training set size, since the optimum look-back horizon tends to vary during the peak wind power.

4. The developed models are recommended to be used as analytical tools for the electricity aggregator development in Latvia.
5. Such results can be a valuable input for analysis on necessity for compensation between aggregators and balance responsible parties or basis for further analysis for policy makers when considering necessity for state support to accelerate introduction of the service.

3.2 Characteristics and trends of electricity export, import, consumption indicators; wind power consumption

As mentioned before, energy markets with high penetration rates of renewables are more likely to face price fluctuations or volatility, which is in part due to the stochastic nature of renewables. The Latvian electricity market is an excellent example of such a market, with over 40 % of Latvia's electricity generation based on hydropower, which disputes the spot electricity price forecast for the Latvian electricity market.

In this part of the Thesis, the author identifies trends in physical and value indicators of total exports, imports, total exchange turnover and electricity consumption in Latvia, and with a more detailed study of the characteristics and trends of indicators of electricity consumption from renewable resources for the period 2014, 2015–2019. Additionally, the indicators of the use of wind electricity were addressed both in general for the observed period and monthly for 2019. Overall, the results of the study confirm the feasibility of Latvia's plans to increase both the total consumption of electricity and its share from renewable sources. At the same time, the coronavirus pandemic has already begun to lead to negative consequences of electricity consumption in the EU countries, which have so far affected Latvia to a lesser extent. Nevertheless, these consequences will inevitably lead to an adjustment of Latvia's electricity plans towards an increase in the share of production and consumption of electricity from renewable sources, including wind energy, despite its upward price trend. The author with employment of the tools of Excel Trendline obtains trends of indicators, approximating formulae dependencies and the coefficients of determination for the relevant diagrams and charts.

Motivation for research

In Latvia, statistics of natural and price indicators of production and consumption of electricity from various types of power plants (PP), including hydro and wind power plants (HPP and WPP), presented in detail. The current analysis of these indicators carried out both in companies related to the production and distribution of electricity, for example[222], and in academic environment[223] .

Trends, indicators and prospects for the development of the Latvian energy sector in combination with climate change for the next decade are reflected in the National Plan of Latvia for 2021-2030.

The author set herself the task of analyzing the dynamics and trends of the indicators under consideration for the period 2014, 2015-2019 – a period ending, on the one hand, with the adoption by the European Union of strategic decisions to combat harmful emissions into the atmosphere and the global transition to the production of electricity using renewable sources, and, on the other hand, the outbreak of the coronavirus pandemic.

The expansion of electricity production from renewable sources will grow only due to the wind power industry, since the hydro power generation capabilities of the Daugava HPP cascade are limited by its design characteristics. The results obtained will serve as a basis for the subsequent identification of trends for the analysed indicators and for the development of appropriate practical recommendations.

Calculation of trends of indicators, approximating formulae dependencies and the coefficients of determination for the relevant diagrams and charts are based on big data collected from the Latvian transmission system operator Augstsprieguma tīkls, Central Statistical Bureau of Latvia, and Nord Pool, the power exchange. The data used in the empirical study is collected from hourly data from the period 1 January 2014 to 31 December 2019. (See Anex1)

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[222] Eurostat. Renewable energy statistics. Statistics Explained [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics; Electricity Market Review by JSC Augstsprieguma tīkls [Online]. Available: http://ast.lv/lv/electricity-market-review [Accessed 05.08.2020]; Prokhorova R. (2020), *AS Covid-19 izraisa pieprasījuma samazinājumu*. Elektroenergijas tirgus apskats Izdevums Nr. 104/ 2020. gada Aprīlis. https://latvenergo.lv/storage/app/media/uploaded-files/ETA_apr_2020.pdf; European Network of Transmission System Operators for Electricity. URL: https://www.entsoe.eu; The Ministry of Economics of the Republic of Latvia. National Energy and Climate Change Plan 2021–2030. URL: https://www.em.gov.lv/lv/nozares_politika/ nacionalais_energetikas_un_klimata_plans/ [Accessed 25.09.2020].

[223] Balodis, M. 2020. *Krīzes ietekme uz enerģētikas nozari Eiropā un Baltijā*. Elektroenergijas tirgus apskats Izdevums Nr. 104/ 2020. gada Aprīlis. https://latvenergo.lv/storage/app/media/uploaded-files/ETA_apr_2020.pdf; Lauka D. 2018. Sustainability analysis of renewable energy sources. Riga: RTU Press; Lauka D., Barisa A., Blumberga D. 2018. Assessment of the availability and utilization potential of low-quality biomass in Latvia. Energy Procedia, 147: 518–524. doi:10.1016/j.egypro.2018.07.065; Lebedeva, K., Krumins, A., Tamane, A., Dzelzitis, E. 2021. Analysis of Latvian Households' Potential Participation in the Energy Market as Prosumers. Clean Technol, 3: 437–449. https://doi.org/10.3390/ cleantechnol3020025; Shipkovs, Lebedeva, K., Migla, L., Kashkarova, G. 2016. Renewable energy resources effective use for rural development. Eng. Rural Dev., 481–487.

The analysis of a small number of selected indicators in the work is carried out using graphs and displaying on them the equations of the trends of these indicators, and the coefficients of determination R^2, obtained by the author using the Trendline Excel toolkit. With a large number of analysed indicators, their display on the graphs is cumbersome; therefore, tables in which the trend equations and the coefficients R2 and R are given – the correlation coefficients between the estimated and observed values of Y and X., accompany the graphs. Trends reflects the dynamics of growth (decrease) of statistical indicators and can be used to forecast them for a short-term period (usually for one period – a month, a year). Regression dependences[224], which makes it possible to qualitatively assess the direction of the trend, were selected by the author from linear equations that, according to observations of *Xi Yi*, have the following general form:

$$Y = bX + a \tag{3.23}$$

where the coefficients *a* and *b* – are the least squares estimates.

Linear regression relationships were used only to assess the qualitative direction of trends. Other types of trends provided by the Trendline Excel toolkit are partially used in the work in order to obtain greater reliability of their direction. Recall that for a linear regression model with one parameter X, the coefficient R^2 is equal to the square of the correlation coefficient between the estimated and observed values of Y and X. In estimating regression models, the value of the coefficient of determination R^2 is interpreted as the model correspondence to the presented data[225].

Electricity generation in the Baltic countries is carried out at condensing and cogeneration heat plants, hydro plants and wind plants. In Estonia and Lithuania, the bulk of electricity is generated predominantly from condensation units fuelled by oil shale and gas, respectively. In Latvia – at cogeneration heat plants and the cascade of the Daugava HPPs, which gives significant competitive advantages in terms of combating environmental pollution. According to[226] the total installed capacity of renewable energy facilities in 2010 and 2018, respectively: in Latvia – 1622 and 1797 MW; in Lithuania – 278 MW and 832 MW; in Estonia – 256 MW and 633 MW. Thus, in Latvia the production of electricity from renewable

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[224] Rawlings, J.O., Pantula, S.G., Dickey, D.A. 2018. Applied Regression Analysis. A Research Tool. 2nd ed. Springer-Verlag NY 7, 21,87,107–110. ISBN 0-387-98454-2

[225] Abdey, J. 2018. *Data Analysis for Management Programme*, Module 6 Unit 1, London School of Economics and Political Science, UK, 8–16.

[226] International Renewable Energy Agency (IRENA), https://irena.org/publications/2019/Jul/Renewable-energy-statistics-2019 [Accessed 07.08.2020]

energy sources (RES) increased insignificantly during this period, while in Lithuania and Estonia this production increased by about 3 and 2.5 times. These countries were forced to significantly increase the production of “clean” electricity in connection with the consequences of the closure of the Ignalina nuclear power plant (Lithuania) and with the phased preparations for the reduction of electricity production from oil shale (Estonia).

All the Baltic countries are experiencing power shortages. Latvia's production covers less than 90 % of electricity consumption, importing it from Lithuania and Estonia, which in turn import it from other European Union countries – Finland, Sweden and Poland. Latvia also carries out imports from third countries – Russia. Average daily generation and consumption of electricity in Latvia depends on many factors, therefore Latvia carries out both imports and exports of electricity, buying and selling it on the Nord Pool electricity exchange. Latvia imports electricity mainly at night and on weekends, when it is cheaper on the market, which allows at this time to reduce the water consumption in the reservoirs of the Daugava HPP cascade and to use the accumulated reserves for production during peak hours. Electricity trade between the Baltic States and other European countries has doubled in the last four years.

The dynamics of statistical physical electricity indicators in Latvia in MWh for the period 2014-2019 is presented in Table 3.20 and shown in Figure 3.1. The following designations of average hourly volumes (MWh) have been introduced: production ($Q1$), consumption ($Q2$), import ($Q3$), export ($Q4$), total exchange turnover ($Q5$) (import + export: $Q5 = Q2 + Q3$) and the excess of import over export ($Q6$) ($Q6 = Q3 – Q4$).

Table 3.20

Electricity generation, import, export and consumption in Latvia, 2014–2019

Indicator MWh (Year)	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Total net electricity production ($Q1$)	4857	5384	6228	4401	6500	6108
Deliveries to the internal market, Consumption ($Q2$)	7172	7201	7263	7278	7408	7226
Import ($Q3$)	5338	5247	4827	4074	5172	4612
Export ($Q4$)	3119	3424	3794	4136	4264	3494
Import-export total ($Q5$)	8457	8671	8621	8210	9436	8106
Import-Export (Q6)	2219	1823	1033	(62)	908	1118

Source: created by the author based on Central Statistical Bureau of Latvia[227]

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[227] Central Statistical Bureau of Latvia. [Online]. Available at: www.csb.gov.lv/en [Accessed 07.08.2020]

As mentioned, the data of Latvian total electricity demand, net electricity production, import and export for the period 2014–2019 is shown on Figure 3.1. There have been no significant fluctuations in final energy consumption over the last decade, moreover, the usage of electricity in 2020 decreased due to the coronavirus crisis (in mid-March, in the Baltic States was declared a state of emergency to limit the spread of the Covid-19 pandemic, which affected electricity demand, especially in the segment of legal entities). In conjunction with the generation increase, the export of electricity has also mostly increased (the correlation of net electricity production and export is notable on the graph). The electricity import is volatile, during the researched time period, however, it is partly relating to export changes. It should be noted that Latvia's export exceeded import in 2017. That year, Latvian domestic electricity production covered 101 % of consumption.

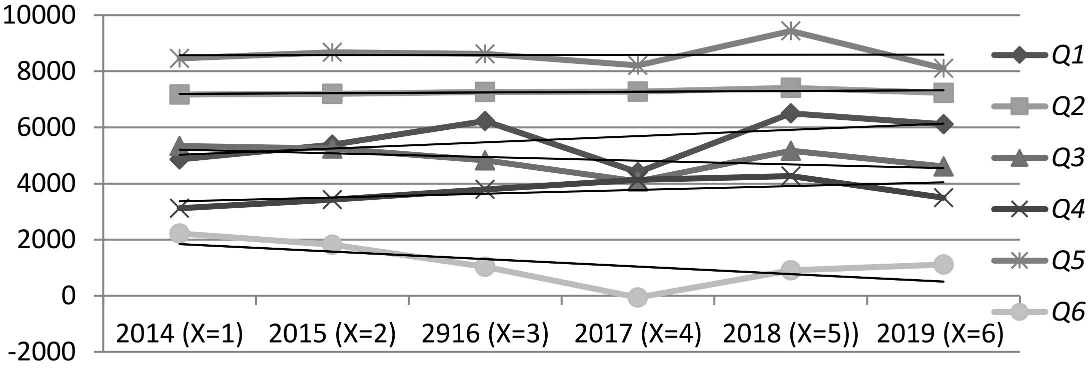

Figure 3.1 **Dynamic of electricity generation, import, export and consumption in Latvia, 2014–2019**

Source: created by the author based on data from Central Statistical Bureau of Latvia[228]

The data in Table 3.20 and Figure 3.1 show that Latvia's electricity imports increase with a drop in the electricity generated at the Daugava HPP cascade due to a drop in water levels in the reservoir. Accordingly, the export of electricity significantly increases with an increase in the generated electricity at the cascade of the Daugava HPPs with an increase in the inflow of water into the reservoir. During the observed period, only in 2017, the volume of exports $Q4$ = 4136 MWh slightly exceeded the volume of imports $Q3$ = 4074 MWh of electricity.

Table 3.21 shows the minimum, average and maximum values of the average hourly indicators Qi, the corresponding trend equations Qti, as well as the values of the coefficients R^2 and R. From Table 3.20 and Figure 3.1 it follows that the annual electricity consumption in Latvia is practically unchanged and averages 7258 MWh, reaching a maximum value of 7408 MWh in 2017 and decreasing to 7226 in 2019.

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[228] ibid

Table 3.21

Minimum, average and maximum values of average hourly indicators
Qi and their Qti trend equations

Indicators	**Qimin**	**Qimax**	**Qimid**	**Equation Qi**	**R^2**	**R**
$Q1$	4401	6500	5580	$Qt1$ = 222.17X +4802.1.1	0.2471	0.5
$Q2$	7172	7408	7258	$Qt2$ = 25.886X + 7167.4	0.339	0.58
$Q3$	4074	5338	4878	$Qt3$ = -131.66X + 5339.1	0.2629	0.51
$Q4$	3119	4264	3705	$Qt4$ = 0.135.34X + 3231.5	0.3294	0.57
$Q5$	8106	9436	8584	$Qt5$ = 3.6857X + 8570.6	0.0002	0.014
$Q6$	(62)	2219	1173	$Qt6$ = -267X + 2107.7	0.398	0.63

Source: created by the author

Note that the closeness of the relationship (according to Scale Cheddoka) between statistical data on these indicators and linear trend equations, expressed by the coefficients R^2, ranges from weak ($Qt1$, $Qt3$) to moderate ($Qt2$, $Qt4$, $Qt6$). These equations can be used for short-term "approximation" of the corresponding indicators for the next year, but not for accurate estimation, since regression models with coefficients R^2, <1 are of low practical value. Electricity production ($Qt1$), consumption ($Qt2$) and export ($Qt4$) trends are upward. The trends in imports ($Qt3$) and the excess of imports over exports ($Qt6$) of electricity are of a downward character, which indicates the dynamics of a slow but decreasing dependence of Latvia on imports of electricity. The trend of the exchange turnover of electricity ($Qt5$) has a neutral character with practically zero coefficient R^2, and the corresponding equation cannot be used for a short-term "approximate" forecast of this indicator.

According to[229] it is noted that the Baltic States are technically able to provide the necessary electricity, but for commercial reasons it is often more profitable to import it due to the high costs of purchasing carbon dioxide emission quotas and the lack of adequate heat load for large natural gas power plants in Riga to operate in economical cogeneration mode.

The Covid-19 pandemic in Europe and the Baltic countries has led to a decrease in electricity consumption by an average of about 10 % since the beginning of 2019 due to a slowdown in economic development[230]. The Baltic countries have seen the smallest decrease in electricity consumption in the European Union: in March and April 2020, consumption decreased by 6.2 % compared to the same period in 2019 (Estonia – by 4 %, Latvia – by 4.3 %,

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[229] Prokhorova, R. 2020. AS Covid-19 izraisa pieprasījuma samazinājumu. Elektroenergijas tirgus apskats Izdevums Nr. 104/ 2020. gada aprīlis. https://latvenergo.lv/storage/app/media/uploaded-files/ETA_apr_2020.pdf

[230] Balodis, M. 2020. *Krīzes ietekme uz enerģētikas nozari Eiropā un Baltijā*. Elektroenergijas tirgus apskats Izdevums Nr. 104/ 2020. gada aprīlis. https://latvenergo.lv/storage/app/media/uploaded-files/ETA_apr_2020.pdf

Lithuania – by 6, 3 %). It is stated that during this period of the pandemic, none of the EU countries violated or worsened the safety of electricity supply, i.e. did not stop the supply of gas and electricity and did not reduce its production. In March 2020, the total electricity generation in the Baltic countries increased by 2 %, while Latvia had the highest electricity generation – 12 % more than in February, and for the first time the production-to-consumption ratio was 107 %, while in Estonia – 48 %, and in Lithuania – 35 %[231].

Let address the dynamics of changes in the total share of electricity produced by HPP and WPP from the total volume of electricity produced for the period 2014–2019 in Latvia. As mentioned in Chapter 1, the scheme of three hydroelectric power plants on the Daugava River (total capacity above 1500 MW) comprises approximately 30 to 50 %[232] of the total annual electrical energy production in the country, but the exact amount differs each year depending on its wetness. Also, one of the cascaded plants (Plavinas HPP) is one of the largest in the European Union by installed capacity[233]. Table 3.22 presents data on the share (%) of electricity generated (without own consumption and losses) in Latvia from renewable sources, which are HPP and WES, obtained by the author by calculation using statistical data from JSC "Augstsprieguma tīkls"[234], Latvian electricity market overview. The share of electricity generated from solar energy was not included. Despite the fact that in 2019 solar power plants produced 3 times more electricity than in 2018, its share (CSB 2019) in the total generated electricity is still insignificant. The total share of HPP and WPP by year is shown in Figure 3.2.

Table 3.22

Shares of electricity generated in Latvia at HPP and WPP, 2014–2019

Indicator (%)	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
HPP (%)	34	30	50	58	37	34
WPP (%)	2.4	2.3	0.7	0.7	1.9	2.5
HPP + WPP (%)	36.4	32.3	50.7	58.7	38.9	36.5

Source: created by the author based on JSC "Augstsprieguma tīkls". Latvian electricity market overview

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[231] Prokhorova, R. 2020. AS Covid-19 izraisa pieprasījuma samazinājumu. Elektroenergijas tirgus apskats Izdevums Nr. 104/ 2020. gada aprīlis. https://latvenergo.lv/storage/app/media/uploaded-files/ETA_apr_2020.pdf

[232] IHA (International Hydropower Association), Hydropower Status Report - Sector Trends and Insights, 2019.

[233] Latvenergo AS, Generation – Facts. [Online]. Available: https://latvenergo.lv/en/parmums/razosana. [Accessed: 21-Mar-2020].

[234] Electricity Market Review by JSC Augstsprieguma tīkls [Online]. Available: http://ast.lv/lv/electricity-market-review [Accessed 05.08.2020]

Figure 3.2 shows the dynamics of changes in the total share of electricity produced by HPP and WPP from the total volume of electricity produced for the period under review in Latvia. The linear trend of this indicator (lower line in Figure 3.2), as well as the logarithmic trend, over the observed period has a neutral character with a barely noticeable increase, but with very low determination coefficients – $R^2 = 0.022$ and 0.0791, respectively.

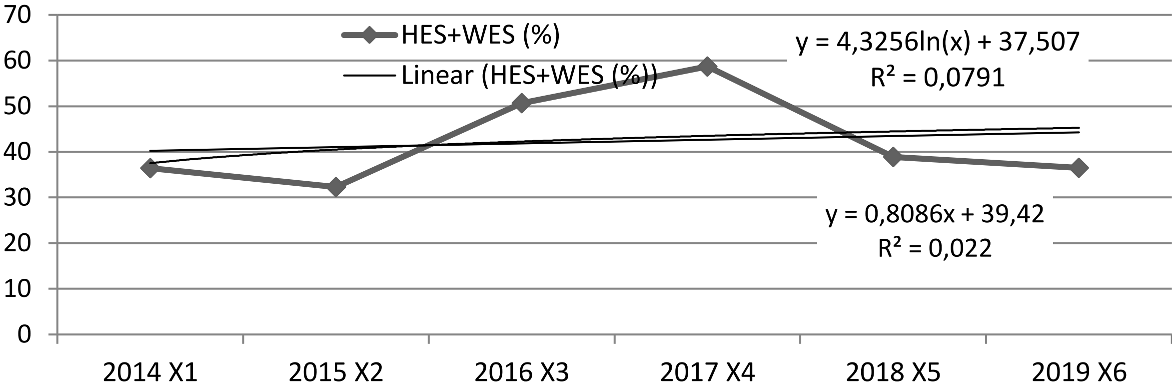

Figure 3.2 **Dynamics of the share of HPP and WPP in the total share of electricity generated in Latvia**

Source: created by the author based on JSC “Augstsprieguma tīkls”. Latvian electricity market overview

From Table 3.22 and Figure 3.2 it follows: firstly, the share of electricity production from RES over these years averaged 42.25 % with a maximum value of 58.7 % in 2017 and a drop in 2018 and 2019; secondly, both the total share and its components are unpredictable; therefore, this trend can be identified more qualitatively from the statistical data of 2020 and 2021. We recall that in accordance with National Energy and Climate Plan of Latvia 2021–2030, the share of renewable energy sources in final energy consumption should grow (in %) in 2020, 2022, 2025, 2027 and 2030, respectively, to 40.95, 41.25, 42.5 43.75 and 45, respectively.

Electricity as any other commodity can be purchased, sold, traded under the rules of electricity market. This is the outcome of worldwide liberalization of power markets. In order to minimize risks, maximize profits and make plans, it is important for participants of electricity market to forecast future prices. In this part data of Latvia’s price zone in Nord Pool power market is analysed. The data set consists of historical hourly electricity prices (Eur / MWh) from January 1, 2014 to December 31, 2019.

In Figure 3.3 shows the dynamics of changes in the average cost (C) of one MWh of consumed electricity in Latvia (European Network of Transmission System Operators for Electricity 2020).

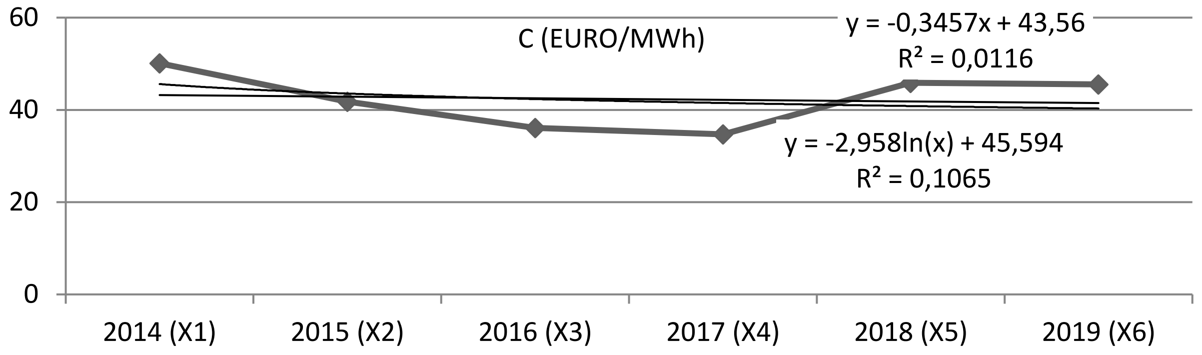

Figure 3.3 **Dynamics of the cost of one MWh for electricity consumers in Latvia, 2014–2019**

Source: created by the author based on (European Network of Transmission System Operators for Electricity 2020[235]

For the period 2014–2015, the indicators of the minimum ($C_{\min}$), maximum ($C_{\max}$), average (C_{mdl}) values are, respectively, 34.7 (2017), 50.1 (2014) and 42.35 EURO / MWh. Linear regression with a very low coefficient of determination $R^2 = 0.0116$ shows a neutral trend in this indicator with a barely noticeable downward trend. Logarithmic regression with a higher coefficient $R^2 = 0.1065$ gives more confidence in the downtrend of the indicator in question. In 2018, the average price on the electricity exchange in the Latvian trade zone was 46.28 EURO / MWh, while the average daily price ranged from 11.99 to 89.45 EURO / MWh.

The current coronavirus crisis, global processes in hydrocarbon production and the hydrological situation in the Nordic countries with heavy rainfall in the Nordic countries influenced the decrease in demand in the region for electricity and became a determining factor in the fall in electricity prices in the first quarter of 2020.[236]

In March, monthly electricity prices continued to decline in all Nord Pool shopping areas. In the Baltic States, the average monthly electricity price, electricity prices have decreased on average by 14 %. The average March price in the Baltic trade zone was about 24 Euro / MWh. It can be assumed that the CX trend, taking into account the results of 2020, will transform from neutral to downtrend.

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[235] European Network of Transmission System Operators for Electricity. URL: https://www.entsoe.eu [Accessed 05.08.2020]

[236] Prokhorova, R. 2020. *AS Covid-19 izraisa pieprasījuma samazinājumu*. Elektroenergijas tirgus apskats Izdevums Nr. 104 / 2020. gada aprīlis. https://latvenergo.lv/storage/app/media/uploaded-files/ETA_apr_2020.pdf [Accessed 07.08.2020]

Wind power consumption characteristics and trends

The situation with wind power plants capacity is different and not only in total Baltic volumes, but in volumes of each country. In 2001 installed capacity of wind power plants was only 2 MW, but following next two years it substantially increased to 24 MW. The next leap when installed capacity increased rapidly to 62 MW in total was in 2012. It can be explained with the start of exploitation period of several wind farms, for instance, 20,07 MW of installed capacity by producer Ltd. “Winergy”. Latvia's total installed capacity of wind turbines in 2019 was about 68 MW. In contrast, in Estonia the installed capacity in 2019 was 310 MW, which is 4,5 times higher than Latvia's. However, Lithuania is absolute leader between Baltic counties with 548 MW installed. (See Figure 3.4). According to the “National Energy and Climate Plan for 2021-2030”, which was prepared by The Ministry of Economics of the Republic of Latvia, Latvia plans to increase the share of RES in electricity generation by increasing the installed capacity of wind generators and solar photovoltaics, taking into account the capacity of Latvia's electricity transmission network, which currently allows to increase the amount of electricity transferred to the network by 800MW.[237] Taking into account the considerations of maritime spatial planning, it is planned to develop joint offshore wind farms projects (with a maximum capacity of 800 MW) on the Latvian-Estonian border and the Latvian-Lithuanian border. The partnership process has already started on September 2020, when The Minister for Economics of Latvia and Estonian Economy and Infrastructure Minister have electronically signed a Memorandum of Understanding on the joint project of the Latvian and Estonian offshore wind farm for energy production from renewable energy sources.

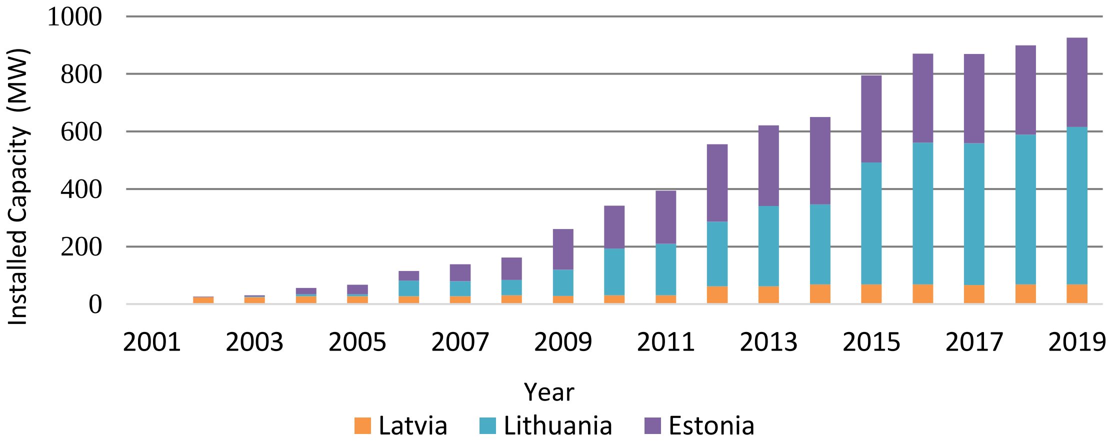

Figure 3.4 **Total Installed Capacity of Latvia’s, Lithuania's and Estonia's Wind Turbines in 2001–2019, MW**

Source: created by the author

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[237] The Ministry of Economics of the Republic of Latvia. National Energy and Climate Change Plan 2021–2030. URL: https://www.em.gov.lv/lv/nozares_politika/nacionalais_energetikas_un_klimata_plans/ [Accessed 25.09.2020]

Figures 3.5 and 3.6 show, respectively, the dynamics of statistical indicators for the planned consumption of wind energy Q_{wes} (MWh) for the day ahead and its cost C_{wes} (EURO / MWh) on the NordPool exchange for Latvia [238]. The observation covers the period from 2015 to 08/20/2020.

The trend of the Q_{wes} indicator (Figure 3.5) with the coefficient $R^2 = 0.7$, also shown in Figure 3.5, has a clearly pronounced upward character with a high strength of connection with statistical data and indicates a steady annual increase in wind power consumption in Latvia.

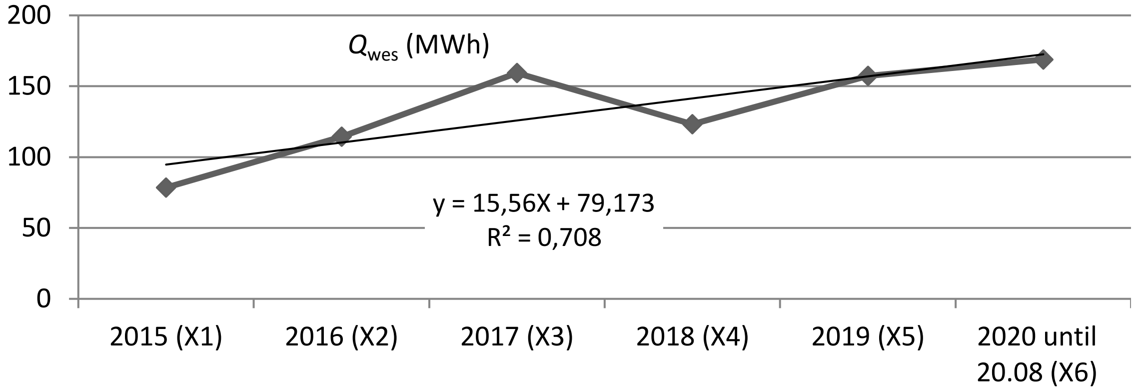

Figure 3.5 **Dynamics of planned wind power consumption for the day ahead in Latvia, 2015–2020**.

Source: created by the author based on (Nord Pool. Market Data 2020)

The upward trend of the C_{wes} indicator, shown in Figure 3.6 by the equation with a high value of $R^2 = 0.7$, in turn indicates a significant increase in the cost of one MWh of wind power consumed in Latvia. Over the past 5 years, this cost has doubled on average. Comparing the data for the comparable period 2015–2019, presented in Figures 3.5 and 3.6, we get: firstly, the corresponding trends are in different directions; secondly, the average cost of consumed wind electricity (123.5 EURO / MWh) is three times higher than the average cost of electricity 40.8 (EURO / MWh) consumed from all PPs. Such ratios are not yet in favour of wind power, and during its development, it is necessary to correlate economic with environmental justifications.

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[238] Nord Pool. Market Data. URL: https://www.nordpoolgroucom/ [Accessed 22.11.2020]

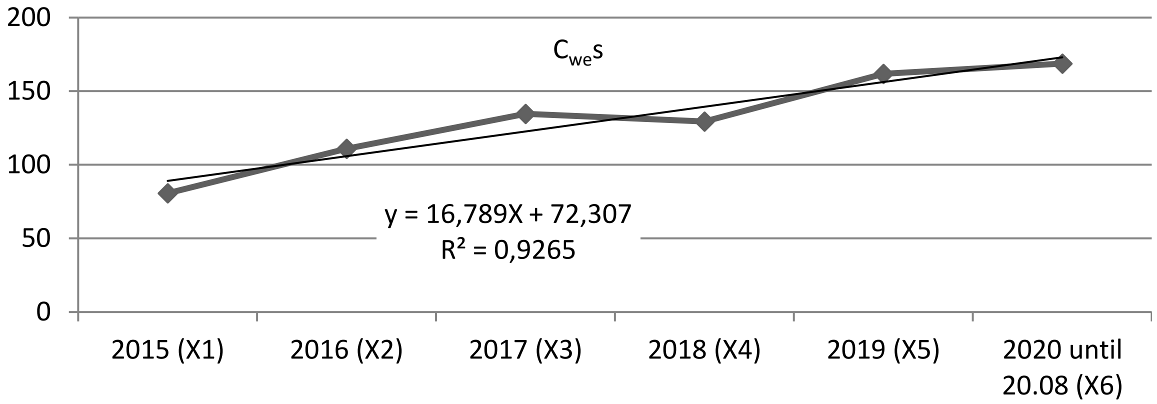

Figure 3.6. **Dynamics of the cost on the NordPool exchange of wind energy planned for consumption for the day ahead in Latvia, 2015–2020**.

Source: created by the author based on (Nord Pool. Market Data 2020)

Let us further investigate in more detail the indicators of consumed wind energy in 2019 during peak hours from 8.00 to 12.00, calculated by the author, based on statistical data.

Table 3.23 shows the author's calculated indicators of the amount of wind electricity planned for consumption the day ahead and its cost on the NordPool exchange in the corresponding month (MWh, EURO / MWh):

- $\hat{W}$, $\hat{C}$ – hourly average;
- $\hat{W}_p$, $\hat{C}_{Wp}$ – average values during peak hours from 8.00 to 12.00.

Table 3.23

Estimated indicators of wind power consumption in Latvia, 2019

Month	$\hat{W}$	$\hat{C}$	$\hat{W}_p$	$\hat{C}_{Wp}$
January	171	57	174	64
February	219	47	211	50
March	222	40	230	43
April	141	44	118	52
May	135	44	123	57
June	89	45	76	66
July	122	49	96	61
August	58	39	47	60
September	161	49	149	67
October	159	47	153	56
November	183	45	181	48
December	224	39	213	42

Source: created by the author based on (Nord Pool. Market Data 2020)

Graphs displaying the dynamics of monthly changes in $\hat{W}$, $\hat{W}p$ (MWh), and $\hat{C}$, $\hat{C}_{\mathrm{Wp}}$ (EURO / MWh) are shown in Figure 3.7 and 3.8.

The graphs of the $\hat{W}$ and $\hat{W}_{\mathrm{p}}$ indicators (Figure 32.7) practically repeat each other, with close monthly values and close averaged values of 157 and 148 (MWh), which indicates that the peak periods practically do not affect the change in the trend of consumed wind energy. At the same time, the months of the year significantly affect the trend of these indicators, which take the lowest values in the warm months from April to September and the highest in the rest of the months.

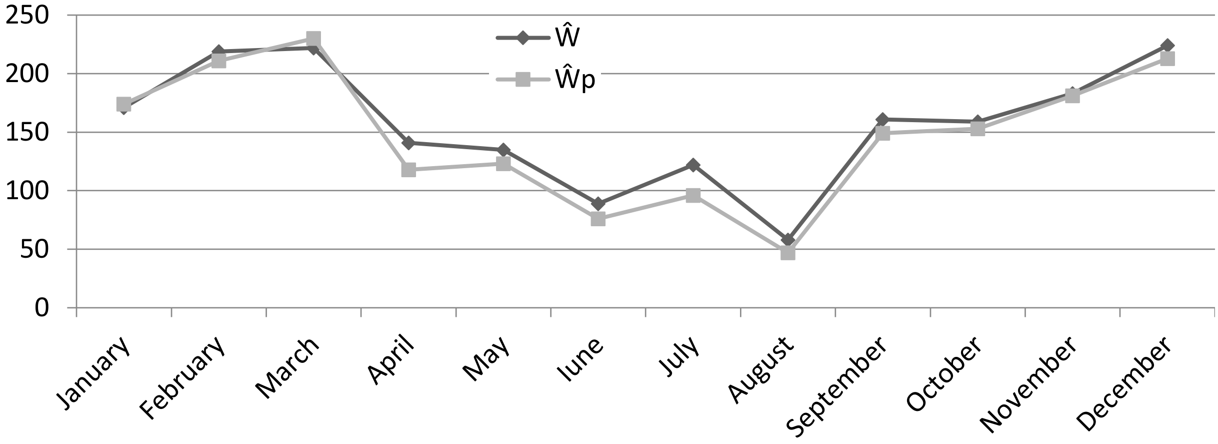

Figure 3.7 **Dynamics of average hourly values of indicators $\hat{W}$ and $\hat{W}_{\mathrm{p}}$ (MWh), 2019**

Source: created by the author based on (Nord Pool. Market Data 2020)

The graphs of the $\hat{C}$ and $\hat{C}_{\mathrm{Wp}}$ indicators (Figure 3.8) are also similar in character. In general, the indicator values during peak hours ($\hat{C}_{\mathrm{Wp}}$) are higher than the average hourly monthly values. Their averaged values 45 and 55 (EURO / MWh) differ by only 18 %.

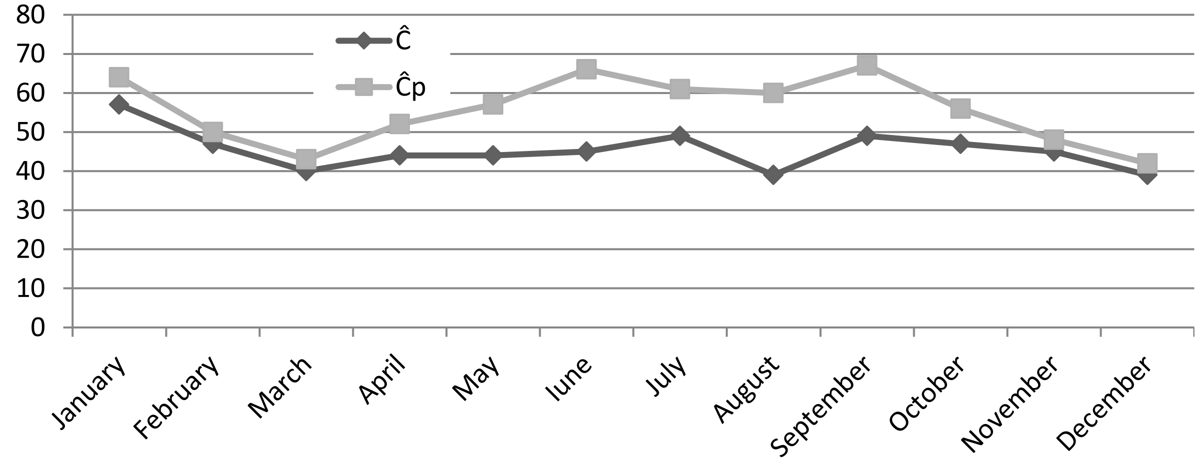

Figure 3.8 **Dynamics of average hourly values of indicators $\hat{C}$ and $\hat{C}_{\mathrm{Wp}}$, 2019**

Source: created by the author based on (Nord Pool. Market Data 2020)

Conclusions

1. Trends in the production, consumption and export of electricity in Latvia are weak, but upward. The trends in imports and the excess of imports over exports of electricity are of a downward nature, which indicates the dynamics of a slow but decreasing dependence of Latvia on imports of electricity. Cannot be used for a short-term "approximate" forecast of this indicator.
2. The trend of planned wind power consumption for the day ahead in Latvia has a clearly pronounced upward character with a high strength of connection with statistical data (coefficient $R^2 = 0.7$) and indicates a steady annual increase in wind power consumption in Latvia, which corresponds to the goals of increasing the share of RES in final energy consumption should grow and reach its share up to 45 % by 2030. At the same time, the upward trend in the cost of one MWh (wind power consumed in Latvia with a high value of $R^2 = 0.7$) does not correlate with the trend in its consumption. This circumstance, as well as the consequences of the coronavirus pandemic, may require adjusting plans to increase electricity consumption from RES, which will require a more detailed assessment of the volume of wind power imports and, possibly, the implementation of measures to increase the capacity for the production of this energy in Latvia.
3. In developing process of a methodology for statistical analysis of wind energy yearly and monthly – for 2019 data, it was established that for practical use should be applied analysis methods that give not only good quality criteria, but also the values of the considered indicators corresponding to the logical meaning. Multiple (polynomial) regression has proven to be an ineffective tool for electricity demand forecasting. One of its main strengths is the negligible computational time it takes to perform forecasts without losing much in terms of accuracy. Furthermore, the forecasting model can be improved by certain modifications, the most promising of which has turned out to be subtraction of the model residuals averaged over hour-of-day.
4. Multiple (polynomial) regression has proven to be an ineffective tool for the analysis of monthly statistical data gave unsatisfactory results, therefore, it is recommended to use the model of sinusoidal dependence of the corresponding indicators on the month number.
5. While other modifications (x component and time series filtration) did not produce a consistently beneficial effect over the whole dataset, there were days when their inclusion aided in improving the accuracy. Thus, a model, which automatically

selects the features the forecasting program, should consider before each daily forecast is advisable. Additionally, it should consider automatic selection of the training set size, since the optimum look-back horizon tends to vary during the peak wind power.

6. The developed models are recommended to be used as analytical tools for the electricity aggregator development in Latvia.

4 The Model for Regulating Electricity Consumption in Latvia on the Basis of Regional Aggregator of Demand Response

The analysis carried out in the 1st, 2nd and 3rd chapters implicate the need of creation of model, of regulating of electricity consumption using Demand Response and customer engagement. Demand Response is considered as a major method that can be taken in order to reduce consumer electrical energy usage when contingencies occur to disturb the balance of supply and demand. DR is introduced as a tariff or program to motivate the end-users in response to changes in the electricity price or to incentive payments which are designed to induce lower electricity consumption when system reliability is jeopardized or during high prices of the wholesale market.[239]

Therefore, ***the goal of this chapter will be: the development of model of a two-stage optimization methodology of regulating of electricity consumption using Demand Response.***

For the implementation of this goal it is necessary:

- to analyse the customers behavioural potential for participation in demand response aggregator, carrying out quantitative research of prosumers in Latvia;
- to suggest the two-stage optimization of the balance of supply and demand, were on the first stage it is proposed to solve the problem of reducing electricity consumption and, at the second stage – to solve the optimization problem of what groups of active consumers loads should be shifted off, if the amount of electricity is not enough and, therefore, in response to electricity market prices.

Thus, the author suggests starting with investigation of the place and role of electricity consumer in the electricity market.

4.1 The role of the energy prosumers in the electricity market and their awareness in Latvia

As it was noted and discussed in the Chapter I, power systems have some inherent undisputable characteristics. Firstly, in real time, supply and demand must always be in balance. Secondly, electric power is not economically storable at a large scale. Moreover, costs of producing electrical energy vary considerably with respect to technology and fuel input. Finally, consumption of electric energy varies over time because of consumer behaviour. Because of these properties, the provision of electricity requires balance management necessary to

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[239] Rashidizadeh-Kermani, H., Vahedipour-Dahraie, M., Shafie-khah, M., Catalão, J.P.S. 2019. Stochastic programming model for scheduling demand response aggregators considering uncertain market prices and demands, International Journal of Electrical Power & Energy Systems, Volume 113, 528–538, ISSN 0142-0615, https://doi.org/10.1016/j.ijepes.2019.05.072. [Accessed 07.08.2020]

safeguard the security of electricity supply from producers to consumers through the electricity network.[240]

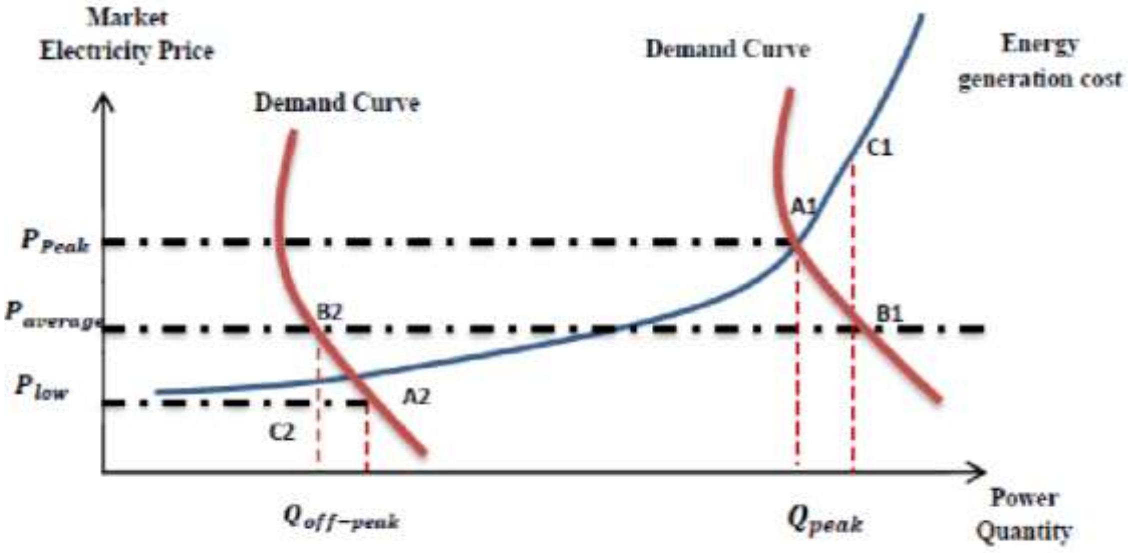

Figure 4.1 **Price volatility reduction by DR**.[241]

Figure 4.1 presents some of the major DR benefits that may be achieved if the DR-capable loads optimize energy consumption. Author also note, that DM resources are also available in the retail electricity market, when, when it is scarce in the Active Customer (AC) region, consumption is reduced. According to the Gellings[242], there is a significant scope for DSM to contribute in increasing the efficiency and use of system assets. Demand side management has been considered since the early 1980s. It can be used as a tool to accomplish different load shaping objectives, such as peak clipping, valley filling, load shifting, strategic conservation, strategic load growth and flexible load shape (see Figure 4.2). Currently consumers have no means of receiving information that would reflect the state of the grid thus could not react to reach the balance and increase efficiency. Due to the nature of renewable, it is not possible to control or request power when it is needed. The main objectives of DR techniques are reduction of peak load and the ability to control consumption according to

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[240] Koliou, E., Eid, Ch., Chaves-Ávila, J.P., Hakvoort, R.A. 2019. Demand response in liberalized electricity markets: Analysis of aggregated load participation in the German balancing mechanism, Energy, Volume 71, 2014, 245-254, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2014.04.067. [Accessed 29 08.2021] Rashidizadeh-Kermani, H., Vahedipour-Dahraie, M., Shafie-khah, M., Catalão, J.P.S. 2019. Stochastic programming model for scheduling demand response aggregators considering uncertain market prices and demands, International Journal of Electrical Power & Energy Systems, Volume 113, 528–538, ISSN 0142-0615, https://doi.org/10.1016/j.ijepes.2019.05.072. [Accessed 29 08.2021]

[241] Teimourzadeh Baboli, Payam & Eghbal, Mehdi & Moghaddam, M. & Aalami, H. 2012. Customer behavior based demand response model. Proc. IEEE Power & Energy Society General Meeting (PES '12). 1–7. 10.1109/PESGM.2012.6345101. [Accessed05.01.2021]

[242] Gellings, C.W. 1985. The concept of demand-side management for electric utilities, Proceedings of the IEEE, 73(10), 1468–1470 CrossRef

generation[243]. Usually, end-users have very little practical knowledge about their flexibility and are unaware of their usage patterns and behaviour. Hence, participants in DR programs show a lower response than the expected levels. Aggregators analyse the end-users' flexibility and advertise financial benefits to engage end-users. The aggregator categorizes the end-users into different groups based on the user's interval energy consumption and usage characteristics, such as the type of appliances used and their DR flexibility, level of involvement, and so forth.

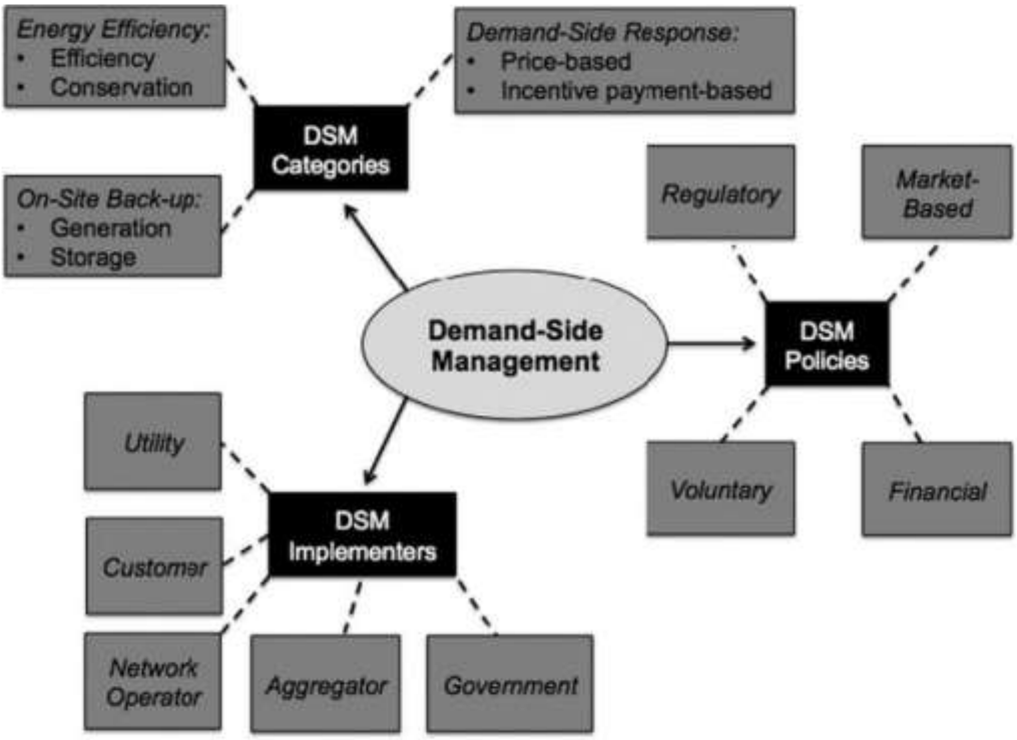

Figure 4.2 **Demand-side Management Elements**[244]

There are three actions a customer can take in response. Customers can reduce load only during critical peak time and maintain normal load pattern during off-peak time. This induces a decrease in customers comfort as they are forced to curtail electricity usage at certain times but reduces the overall consumption thus reducing electricity bill even further. The second action that could be taken in order to respond to high electricity prices or low availability is to offset electricity use from peak to off-peak time. This method would flatten the load shape by both decreasing the peak load and filling low consumption valleys. It does not reduce the average amount of energy used by the end users, but increases the transmission and distribution efficiency as the system operates in more stable mode. Finally, customers can use on site generation to reduce demand seen by the utility. This would increase user autonomy, further

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[243] Gelazanskas, L., Gamage, K.A.A. 2014. Demand side management in smart grid: A review and proposals for future direction, Elsevier, Sustainable Cities and Society, vol. 11, 22–30,

[244] Warren, P. 2014. A review of demand-side management policy in the UK, Renewable and Sustainable Energy Reviews, vol. 29, 941–951.

decentralize generation and decrease average load on distribution and transmission grids. On the other hand, it would maximize system complexity[245]. DR aggregator should be coordinated with a customer's temporal order of activities and schedules. Notably, the residential customers have some crucial factors that should be duly considered. Deferring household activities and appliances rescheduling sometimes affect dependent activities and should be practically and carefully managed when adopting beneficial technology in a smart grid to improve the grid's functionality[246]. To participate in DR programs, the users must reveal their willingness, preference, in-home activity data, and so forth, which may breach privacy[247].

The role of "citizen energy" in the energy perspective in the EU energy transition process could be remarkable: over 112 million energy citizens could provide up to 19 % of Europe's electricity demand by 2030; by 2050, this could increase to up to 45 % of total electricity demand, including collective projects up to 37 %[248].

The movement of prosumers in Latvia is at an early stage of development. However, there are various initiatives, including small enterprises, municipal, and individual citizens that incorporate the features of energy prosumers or renewable energy source (RES) projects. Various RES-s are used for electricity generation in the residential sector, such as solar and wind energy[249]. Up to June 2020, the Ministry of Economics (ME) had issued 282 permits to increase electricity generation capacity or introduce new generation facilities that do not meet the requirements for microgenerator connections[250]. According to the information of the ME on issued permits, 46 % of them use solar energy and 30 % use wind energy to generate electricity; the rest also use RES hydropower or biomass cogeneration plants. Thirty-seven percent of electricity is produced for their own consumption, and only 4 % of the permits have been for households and other legal entities[251].

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[245] Gelazanskas, L., Gamage, K.A.A. 2014. Demand side management in smart grid: A review and proposals for future direction, Elsevier, Sustainable Cities and Society, vol. 11, 22–30.

[246] Kim, J. H., and Shcherbakova, A. 2011. Common failures of demand response, *Energy*, vol. 36, no.2, 873–880. [Accessed05.01.2021]

[247] Lisovich, M.A., Mulligan, D.K., and Wicker, S.B. 2010. Inferring personal information from demand-response systems, *IEEE Secur. Priv.*, vol. 8, no. 1, 11–20. [Accessed 05.01.2021]

[248] Kampman, B.E., Blommerde, J., Afman, M.R. 2016. The potential of energy citizens in the European Union. Ce Delft Available online: https://www.cedelft.eu/en/search?q=The+potential+of+energy+citizens+in+the+European+Union.++ (accessed on 4 December 2020).

[249] Lebedeva, K., Krumins, A., Tamane, A., Dzelzitis, E. 2021. Analysis of Latvian Households' Potential Participation in the Energy Market as Prosumers. Clean Technol., 3, 437–449. https://doi.org/10.3390/cleantechnol3020025[Accessed 05.01.2021]

[250] Bogdanovičs, R., Borodinecs, A., Zajacs, A., Šteinerte, K. 2018. Review of Heat Pumps Application Potential in Cold Climate. Adv. Intell. Syst. Comput., 543–554. [Accessed 05.01.2021]

[251] Latvian Ministry of Economics: Permits for the Introduction of New Electricity Generation Facilities. Available online: https://www.em. gov.lv/lv/nozares_politika/atjaunojama_energija_un_kogeneracija/atlaujas_jaunu_elektroenergijas_razosanas_iekartu_ieviesanai/ (Accessed 04.12.2020).

Prosumer's Awareness in Latvia

In order to investigate truthfulness of theoretical part of project, it is reasonable to conduct quantitative research among prosumers for better comprehension of definition of prosumers, the sense of electricity, type of energy used and produced by prosumers, heating types and other factors.

The goal of this analysis is to explore the level of awareness of Latvian consumers of electricity about prosumerism, willingness of people who are well aware of the concept to engage in the process and to recognize the main electricity consumption factors that may lead to it.

The survey was open to everyone interested in participating, however, the sample was not representative of the Latvian population because the aim was mainly to learn about the level of an awareness of Latvian consumers of electricity about prosumerism, and thus, about potential for engagement in demand response in Latvia. Representative data would enable more detailed analyses about the willingness and motives of different types of consumers to take part in demand response. Further, the differences in the preferred information channel on electricity consumption and prices could be analysed. Finally, because of the survey method, it is possible that the respondents were more interested in energy issues than average residential consumers. The survey is thus susceptible to the same self-selection bias identified in other surveys and pilots about demand response or energy issues in general.

The study of the preferences of consumers (See Chapter 1.1. Genesis of DR) has been limited to the preferred set-up time for the scheduling of appliance operations or air or water temperatures, so there are no any approaches in the literature that assist the end-user to aggregate the total preferences regarding all effective parameters in energy consumption. In the methodology part, it is intended to apply quantitative method, which is valuable to gather respondents' opinion through numeric data. In differ from qualitative method, quantitative allows to amass replies and make correlation between independent and dependent variables by coded information. Initially step is to prepare questionnaire (see Annex 2) which is considered one of research tool for quantitative method. After construction of the tool, questionnaire was forwarded to random respondents through social media channel. As the final stage, it was collected replies from 108 respondents. After taking interview from prosumers, their answers were codded and inserted into Excel file that has been dragged by numeric way then to SPSS program. For obtaining the coefficient of reliability was used the Cronbach's alpha test (with the value, the module of which is between 0 and 1, which is carried out, using the SPSS programs).

The coefficient of reliability is an important criterion for the evaluation of test results. It is a measure of accuracy with which is carried out the testing of some feature. In calculation was used the SPSS program, the Cronbach's Alpha with the value, the module of which is between 0 and 1.

The standardized Cronbach's alpha coefficient α_{st} is calculated by formula:

$$\alpha_{st} = \frac{N \cdot \bar{r}}{1 + (N - 1) \cdot \bar{r}} \qquad (4.1.)^{252}$$

Where N is the number of the researched components, but determines the average coefficient of the correlation between the components.

Results of investigation

Demographical factors: Gender and age group

According to Table 4.1 extracted from the crosstabulation test there were 108 respondents who took a part in survey where 65 were male while representative of females reaches to just 43. Along with gender, another type of demographical factor of research can consider age group with five dimensions. Referring to bar chart, most of respondents belong to 27–36 aged group that exceed in amounts two rest of age groups (47 to 56, 57 and above). The numbers of females couldn't exceed males at all age group.

Table 4.1

Respondents' answers, to question: "What is your gender? * Which age groups do you belong?" Crosstabulation [253]

Count		**Which age groups do you belong?**					**Total**
		17 to 26	**27–36**	**37–46**	**47 to 56**	**57 and above**	
What is your gender?	Male	19	21	18	4	3	65
	Female	10	16	14	2	1	43
Total		29	37	32	6	4	108

Source: created by the author

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[252] Abdey, J. 2018. Data Analysis for Management Programme, Module 6 Unit 1, London School of Economics and Political Science, UK, 8–16.

[253] In this part of the thesis from this point all tables and figures are made by the author.

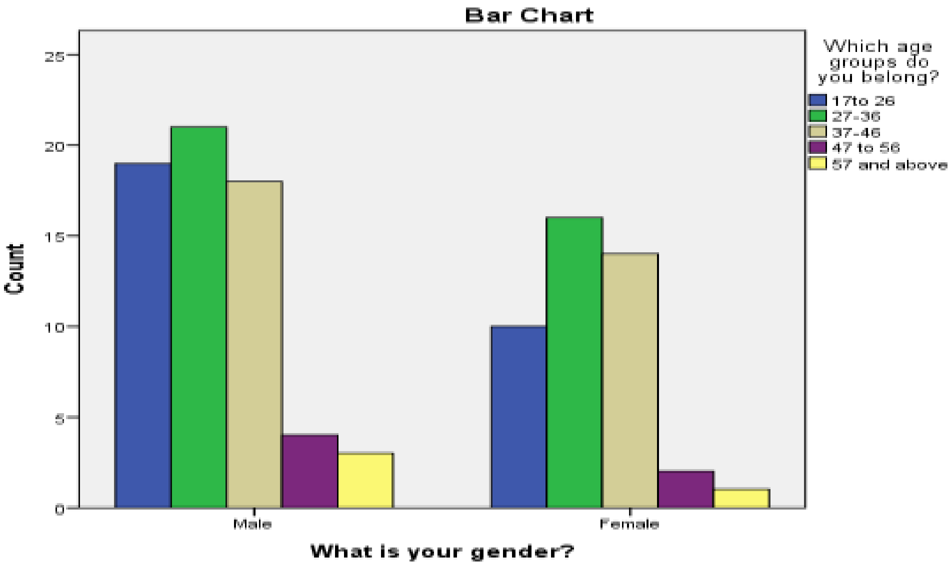

Figure 4.3 **Respondents' answers to the questions: "What is your gender? * Which age groups do you belong?"**

Source: created by the author

Being prosumer

Prior to commence of exploration the sense of self-generation electricity, is mandatory to identify in what extend respondents consider themselves as a prosumer. Frequency test of SPSS analysis allows determining the level of each items separately. Based on bellow demonstrated Table 4.2, 39.8 % of respondents is familiar with the definition of prosumer moderately. Another high statistic figure (36.1 %) pertains to respondents with high level of awareness of prosumer. The statistics demonstrate that respondents are well aware of the notion of prosumer, only some of participants (2.8 %) have a very low level of knowledge concerning this issue.

Table 4.2

Frequency test of SPSS analysis to the respondent's' answer, to question: "To what extend you consider yourself a prosumer"?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Very low level	3	2.8	2.8	2.8
	Low level	8	7.4	7.4	10.2
	Medium level	43	39.8	39.8	50.0
	High level	39	36.1	36.1	86.1
	Very high level	15	13.9	13.9	100.0
	Total	108	100.0	100.0	–

Source: created by the author

Consumption of electricity

This section of analysis involves itself:

a) frequency of usage electricity
b) satisfaction with electricity provider and
c) compliance of self-generated electricity with demand
d) counting of volume of electricity embraces this topic as well.

a. Frequency of usage of electricity

Cross tabulation test contributes to correlate age group with frequency usage variable. Options were designed by scale method from very often to seldom items. Primarily, it is necessary to point out that user need often extra electricity. However, 7 respondents indicated seldom demand in additional energy. Frequency of usage of electricity will varied in dependence of age group. According to the table, respondents with middle age (27–36) and (37–46) frequently demand in additional electricity sources. However supplementary electricity is not at interest of 57 and above years old participants.

Table 4.3

Respondents' answers, to question: "Which age groups do you belong? * How often do you need extra electricity?" Crosstabulation

Count		**How often do you need extra electricity?**				**Total**
		Very often	**Often**	**Sometimes**	**Seldom**	
Which age groups do you belong?	17 to 26	7	10	6	6	29
	27–36	10	19	8	0	37
	37–46	8	16	7	1	32
	47 to 56	3	3	0	0	6
	57 and above	1	2	1	0	4
Total		29	50	22	7	108

Source: created by the author

b. Satisfaction with electricity provider

Chi-square test depicts that 28 males out of 65 express own satisfaction from electricity provider. Almost the same results are observed at female replies during interview (21 satisfied). On the other hand, unsatisfied ratings are excessively high amid males (14) rather than females (7). (Table.4.4).

Table.4.4

Respondents' answers, to question: "To what extent you are satisfied with your electricity provider? * What is your gender?" Crosstabulation

Count		**What is your gender?**		**Total**
		Male	**Female**	
To what extent you are satisfied with your electricity provider?	Very unsatisfied	5	4	9
	Unsatisfied	14	7	21
	Neutral	9	10	19
	Satisfied	28	21	49
	Very satisfied	9	1	10
Total		65	43	108

Source: created by the author

For further analysis of the data we have conducted an independent sample test by using SPSS, the author has calculated Leven's test for equality of variance and t-test for equality of means. The author has tested Null hypothesis that two means are equal. Test variables were Male and Female. The Levene's Test for equality of variances tells us if we have met our second assumption, i.e. the two groups have approximately equal variance for these two variables. If the Levene's Test is significant (the value under "Sig" is less than 0.05), the two variances are significantly different. If it is not significant (Sig. is greater than 0.05), it means the two variances are approximately equal. If the Levene's test is not significant, we have met our second assumption. Here we can assume that the variances of these two variables between the two groups are approximately equal. Implementation of independent sample test evident that there is not significant difference between males and females. P value equals to .497/.486 that are more than alpha (0.05) that shows absence of correlation between satisfaction and gender. (Table.4.5).

Table 4.5

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95 % Confidence Interval of the Difference	
									Lower	Upper
To what extent you are satisfied with your electricity provider?	Equal variances assumed	1.787	.184	.682	106	.497	.152	.224	-.291	.596
	Equal variances not assumed	–	–	.699	97.359	.486	.152	.218	-.280	.585

Source: created by the author

c. Compliance of self-generated electricity with demand

This question relates to five scale Likert options that involve answers varied from strongly disagree to strongly agree. Frequency test assists to analyse in what extend respondents give consent to self-generated electricity idea. Most of respondents selected agree scale (51.9 %), another huge percent refers to neutral option (19.4 %). Only eight participants ticked disagree box (7.4 %). (Table.4.6).

Table 4.6

Frequency test of SPSS analysis to the respondents' answer, to question:
"To what extent you agree that self-generated electricity is the better option?"

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Strongly disagree	14	13.0	13.0	13.0
	Disagree	8	7.4	7.4	20.4
	Neutral	21	19.4	19.4	39.8
	Agree	56	51.9	51.9	91.7
	Strongly agree	9	8.3	8.3	100.0
	Total	108	100.0	100.0	–

Source: created by the author

d. Volume of electricity

Volume of electricity will lead to figure out how many kilowatt hours prosumers will spend within month. 38 participants of interview stated that month volume of electricity ranges from 200 to 250. (table 4.7) 21.3 answers illustrates that they utilized more than 250 kilowatt per month. Only 11 respondents use less than 150 Kw and merely six respondents indicate that more they used plenty numbers of kilowatts that were least statistics in this test. (table 4.7)

Table 4.7

Frequency test of SPSS analysis to the respondents' answer, to question: "How many kilowatt-hours of electricity do you use monthly?"

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Below 150	11	10.2	10.2	10.2
	150 to 200	30	27.8	27.8	38.0
	200 to 250	38	35.2	35.2	73.1
	250 to 300	23	21.3	21.3	94.4
	More than 300	6	5.6	5.6	100.0
	Total	108	100.0	100.0	–

Source: created by the author

Types of energy preferred by prosumers

There are four types of energy that is given preferences by prosumers. Residential is first type of energy that produced on own property by installing solar PV panels. This is most popular type of energy preferred by prosumers (37 out of 108 respondents). Following tables shows that about 15 % people are using solar panels technology, 27 % are using warm air system, 39 % are using storage heaters and almost 27 % are using gas-fired boilers, they are mostly used in industries.

Awareness of solar panel technology and its function

Most of respondents are familiar with solar panel technology (59.3 %); on the other hand, there is not significant difference between yes and no answers. It may identify that half numbers of participants get to know concern of solar technology while others don't have any mind regarding this type of energy (40.7 %). (Table 4.8)

Function of solar panel technology. Based on Table 4.9, most of respondents have challenges to understand the functions and way of operations of solar panel technology (54 out of 108). On the other hand, the similar data was observed amid respondents (54 out of 108) point that solar panel system is easy technology for usage.

Table 4.8

Frequency test of SPSS analysis to the respondents'' answer, to question: "Are you familiar with solar panel technology?"

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Yes	64	59.3	59.3	59.3
	No	44	40.7	40.7	100.0
	Total	108	100.0	100.0	–

Source: created by the author

Table 4.9

Respondents' answers, to question: "Do you know how solar panel technology works? * What is your gender? Crosstabulation

Count		What is your gender?		Total
		Male	Female	
Do you know how solar panel technology works?	Yes	30	24	54
	No	35	19	54
Total		65	43	108

Source: created by the author

Heating types

This question has important sense in recognition the prosumers preference in terms of heating types. Referring to questionnaire it is evident that there are four various types of heating: Gas-Fired boiler, storage heaters, warm air system and solar panels. Storage heaters (39) are ideal option for most of prosumer to warm up own houses. Gas fired boiler (27) are mostly used in industries and central heating or warm air system (27) will heat up prosumers house. Solar panel is less demanded types of heating, there were 15 people preferred it.

Frequent usage of heater in winter. Along with determination types of heating by prosumers, awareness of frequent usage of heater during winter will be significant in analysis of electricity. Based on Table 4.10, it should infer that 38.9 % of users frequently utilize heater within winter. Only three out of 108 respondents very rarely use heater in household. Statistics shows that 20.4 % from all respondents indicate sometimes option.

Table 4.10

Frequency test of SPSS analysis to the respondents' answer, to question: "How often do you / your household use a heater in winter?"

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Very often	32	29.6	29.6	29.6
	Often	42	38.9	38.9	68.5
	Sometimes	22	20.4	20.4	88.9
	Rarely	9	8.3	8.3	97.2
	Very rarely	3	2.8	2.8	100.0
	Total	108	100.0	100.0	–

Source: created by the author

Use of heater in duration of day

This question should be analysed through chi-square test where correlation between independent (males, females) and dependent variables (type of the day) stands in the foreground. Follow the data illustrated bellow (table 4.11) it may reveal that males use heater in the evening (17) and at night (22). Current condition is inherent for representatives of females as well. However, all the day male spend more energy than females.

Table 4.11

Respodents' answers, to question: "At what time of the day do you usually use your heater? * What is your gender?" Crosstabulation

Count		What is your gender?		Total
		Male	Female	
At what time of the day do you usually use your heater?	Morning	5	6	11
	Afternoon	7	8	15
	Evening	17	12	29
	Night	22	12	34
	All-day	14	5	19
Total		65	43	108

Source: created by the author

Role of air conditioner in prosumers life

Being one of variety of energy, the sense of air container seems tremendous. Unlike to heater, it is significant to measure the level of utilization of air conditioner. Table. 4.12 is oriented on analysis of air conditioner during summer, where frequent and very often answers reached to 76 and exceed to rests of options.

Table 4.12

Frequency test of SPSS analysis to the respodents' answer, to question: "How often do you / your household use an air conditioner in summer?"

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Very often	40	37.0	37.0	37.0
	Often	36	33.3	33.3	70.4
	Sometimes	24	22.2	22.2	92.6
	Rarely	4	3.7	3.7	96.3
	Very rarely	4	3.7	3.7	100.0
	Total	108	100.0	100.0	–

Source: created by the author

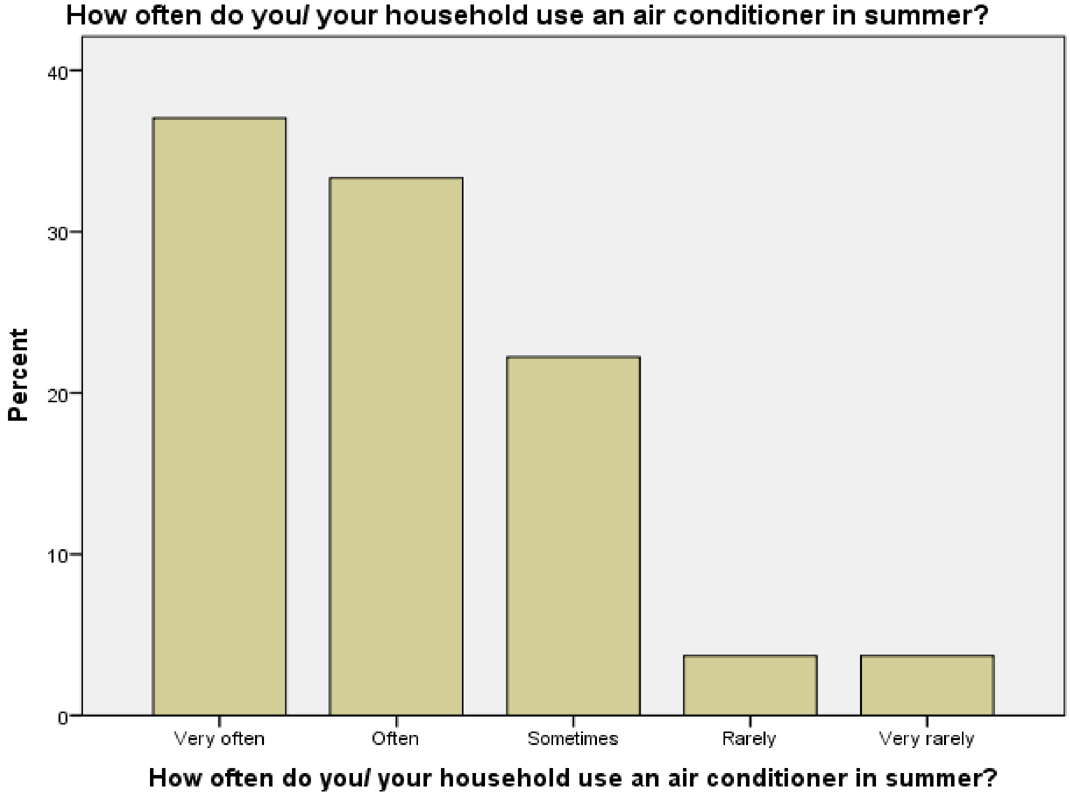

Figure 4.4 **Respodents' answers, to question: "How often do you / your household use an air conditioner in summer**

Source: created by the author

Use of air conditioner can vary in duration of the day. Table 4.13 points out that evening is appropriate day of time for prosumers. Other huge rates can observe afternoon and night option. Morning is least result that shows prosumers consume little volume of energy.

Table 4.13

Frequency test of SPSS analysis to the respodents' answer, to question: "What time of the day do you usually use your air conditioner?"

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Morning	15	13.9	13.9	13.9
	Afternoon	28	25.9	25.9	39.8
	Evening	40	37.0	37.0	76.9
	Night	25	23.1	23.1	100.0
	Total	108	100.0	100.0	–

Source: created by the author

Table 4.14

Frequency test of SPSS analysis to the respodents' answer, to question: "To what extent you agree to make your home more energy efficient?"

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Strongly disagree	12	11.1	11.1	11.1
	Disagree	6	5.6	5.6	16.7
	Neutral	22	20.4	20.4	37.0
	Agree	54	50.0	50.0	87.0
	Strongly agree	14	13.0	13.0	100.0
	Total	108	100.0	100.0	–

Source: created by the author

Conclusion:

Having said that, the conclusion of a qualitative study can at times be quite detailed. This would depend on the complexity of the study. A questionnaire about likes and dislikes is simpler to score, interpret, and infer than a focus group, interview, or case study. In the case of a simpler study, you may reiterate the key findings of the study in the conclusion.

According to the table extracted from the crosstabulation test, 108 respondents took part in a survey where 65 were male while representative of females reached only 43 Along with gender, another type of demographic factor of research can consider age group with five dimensions. Referring to the bar chart, most respondents belong to the 27–36 aged group that exceed in amounts two rest of age groups (47 to 56, 57 and above). The numbers of females exceed males among the 37–46 age group.

Being a prosumer. Prior to commencing of exploration, the sense of self-generation electricity is mandatory to identify how respondents consider themselves a prosumer. The frequency test of SPSS analysis allows determining the level of each item separately. Based on the results, 39.8 % of respondents are familiar with the prosumer's definition moderately. Other high statistics (36.1 %) pertain to respondents with a high level of awareness of prosumer. Statistics demonstrate that respondents are well known with the notion of prosumer; only three participants (2.8 %) has a very low level of knowledge.

The level of awareness prosumerism of the respondents who participated in the survey is relatively high. Although, the author suggests that those who are not familiar with the term prosumerism simply did not continue to fill out the questionnaire.

It is important to note that the behaviour of electricity consumers testifies to the great potential of Latvian consumers to participate in the electricity generation and sale market. This means the potential to participate in the aggregation of electricity demand.

The survey was open to everyone interested in participating, however, the sample was not representative of the Latvian population because the aim was mainly to learn about the level of an awareness of Latvian consumers of electricity about prosumerism, and thus, about potential for engagement in demand response in Latvia. Representative data would enable more detailed analyses about the willingness and motives of different types of consumers to take part in demand response. Further, the differences in the preferred information channel on electricity consumption and prices could be analysed. Finally, because of the survey method, it is possible that the respondents were more interested in energy issues than average residential consumers. The survey is thus susceptible to the same self-selection bias identified in other surveys and pilots about demand response or energy issues in general

4.2 Development of the model of a two-stage optimization of regulating of electricity consumption using Demand Response

Motivation for the Research

The rapid development of renewable energy and its integration into the energy system, the growing requirements of modern industry with a high level of digitalization to the quality of energy supply, as well as the widespread introduction of energy-saving technologies dictate the need for a radical renewal of the energy grid economy through the large-scale development of smart grids. Smart Grid is seen as a fully integrated, self-regulating and self-healing power system with a network topology and including all generating sources, trunk and distribution networks and all types of consumers of electrical energy, controlled by a single network of information and control devices and systems in real time. One of the key functional characteristics of the Smart Grid concept is the motivation of the active behaviour of the end user, which is understood as providing the possibility of independent change by consumers of the volume and functional properties of the electricity received based on balance of their needs and capabilities of the power system using information on the characteristics of prices, volumes of electricity supplies, reliability, quality, etc.[254]

Within the framework of the developed Smart Grid concept, the diversity of the requirements of all interested parties (government, consumers, regulators, energy companies, companies, sales and utilities organizations, owners, equipment manufacturers, etc.) is reduced to a group of key requirements (values) of the new electric power industry, formulated as: availability, reliability, economy, efficiency, environmental friendliness and safety.[255] The well-known technical and economic advantages of smart grids include a reduction in technological losses during power transmission, the ability to smooth out power consumption peaks and thereby reduce the volume of reserve generating capacities, the ability to connect to the network a significant number of generating sources with unstable operating modes, including micro-generating devices belonging to consumers, as well as automation of the functions of monitoring energy supply and metering of energy consumption. In addition, the development of the Smart Grids can achieve such positive social effects as reducing the burden on the environment by increasing the efficiency of the entire energy supply system.

Power systems have some inherent undisputable characteristics. Firstly, in real time, supply and demand must always be in balance. Secondly, electric power is not economically storable at a large scale. Moreover, costs of producing electrical energy vary considerably with respect to technology and fuel input. Finally, consumption of electric energy varies over time on account of consumer behaviour. As a result of these properties, the provision of electricity requires balance management necessary to safeguard the security of electricity supply from producers to consumers through the electricity network.[256]

Currently, the energy industry in the EU countries, as well as around the world, is undergoing a transformation in which consumers use, store or sell their own electricity or participate in Demand Management (DM) and energy efficiency schemes, thus transforming themselves into active consumers. At the same time, the number of active consumers of electricity (industrial, commercial, agricultural and household consumers) under DM

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[254] ANEC and BEUC. 2011. Position on Energy Efficiency. Joint ANEC BEUC position paper on the Commissions Communication Energy Efficiency Plan 2011. Retrieved from http: www.becu.org publications 2011-00397-01-e.pdf [Accessed 21.09.20]

[255] Vesnic-Alujevic, L., Breitegger, M., Guimarães Pereira, Â. 2016. What smart grids tell about innovation narratives in the European Union: Hopes, imaginaries and policy, Energy Research & Social Science, Volume 12, 16–26, ISSN 2214-6296, https://doi.org/10.1016/j.erss.2015.11.011. [Accessed 21.09.20]

[256] Koliou, E., Eid, Ch., Chaves-Ávila, J.P., Hakvoort, R.A. 2014. Demand response in liberalized electricity markets: Analysis of aggregated load participation in the German balancing mechanism, Energy, Volume 71, 245–254, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2014.04.067. (https://www.sciencedirect.com/science/article/pii/S0360544214004800)

conditions should become quite massive.[257] Voluntary optimization of electricity consumption by the end user with a certain economic benefit[258] is carried out by the Demand Response (DR) mechanism.

In optimized consumption, higher peaks clip, and lower valleys fill by rescheduling electric appliances and energy usage over a time horizon in response to a DR signal.[259] Figure 4.5 presents some of the major DR benefits that may be achieved if the DR-capable loads optimize energy consumption Author also note that DM resources are also available in the retail electricity market, when, when it is scarce in the Active Customer (AC) region, consumption is reduced.

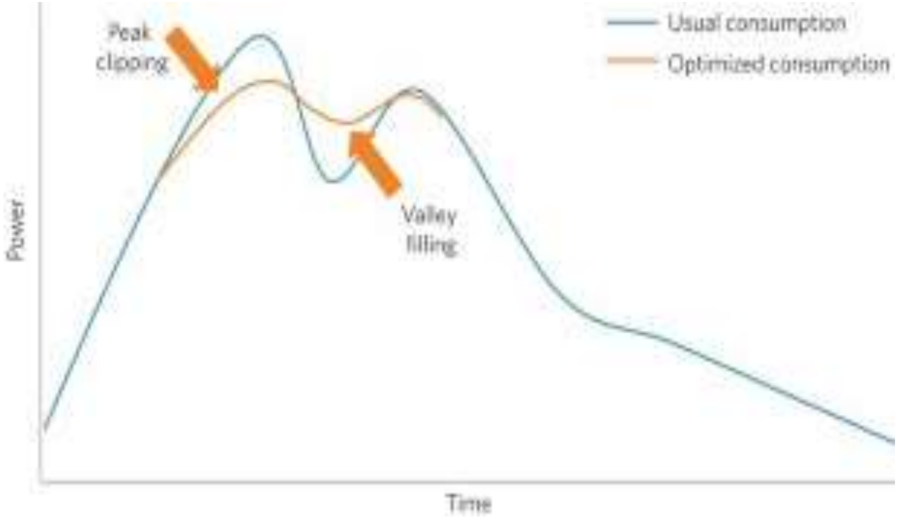

Figure 4.5 **Graphic visualization of the demand response concept in relation to electricity consumption showing usual consumption and optimized consumption**[260]

Objectives in Optimization

Optimization of DR mechanisms obtains the best possible variables to maximize or minimize an objective function value, if the variables are bounded by a set of constraints[261].

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[257] Stede, J., Arnold, K., Dufter, Ch., Holtz, G., Roon, S. von, Richstein, J.C. 2020. The role of aggregators in facilitating industrial demand response: Evidence from Germany, Energy Policy, Volume 147, 111893, ISSN 0301-4215, https://doi.org/10.1016/j.enpol.2020.111893. (https://www.sciencedirect.com/science/article/pii/S030142152030608X)

[258] An incentive is a cost or benefit that motivates a decision or action by end-user customers, businesses, or other commercial and regulated parties. Incentives aim to provide value for money and contribute to reaching set objectives. These can be created temporarily (short term) or to support long term strategies. Incentives could be targeted on specific consumer groups, on regulated entities (e.g. grid operator), or on non-regulated entities (commercial market parties). – Smart Grid Task Force, Regulatory Recommendation Report, January, 2015.

[259] ibid

[260] Leal-Arcas, R., Lesniewska, F., Proedrou, F. 2017. Smart grids in the European Union: Assessing energy security, regulation & social and ethical considerations.

[261] Vardakas, J.S., Zorba, N., and Verikoukis, C.V. 2014. A Survey on Demand Response Programs in Smart Grids: Pricing Methods and Optimization Algorithms, *IEEE Commun. Surv. Tutorials*, vol. 17, no. c, 1–1.

Optimization problems can be categorized according to several criteria. Depending on nature (degree in the polynomial form of the function) of the objective functions and constraints, involved, linear and nonlinear optimization exists. If at least one of the objective functions and / or constraints is nonlinear, the problem is said to be nonlinear optimization. A mixed integer programming problem denotes whether some of the variables are integers. Additionally, based on the nature of the variables (deterministic or the stochastic) involved, optimization problems can be classified into deterministic and stochastic programming problems; the latter case describes optimization models that deal with RES, due to the stochastic nature of these sources.[262]

As have been mentioned in the first chapter, all EU countries both buy and sell electricity on the NordPool exchange. Many of them, including Latvia, import more electricity than they sell. Therefore, the optimization of the balance of supply and demand is an important task, for the solution of which a two-stage optimization methodology is proposed.

A crucial factor that must not be forgotten when developing mathematical optimization models, however, is their ease of implementation and peculiarities caused by application to a particular system. In other words, to have a practical purpose the mathematical model has to be implemented in an actual software tool, which can be deployed on an Aggregator operator's workstation and would allow the software to utilize it.

Thus, at the first stage, based on predicted data on the shortage of electricity for the next day, it is proposed to solve the problem of reducing its consumption. At the second stage, the choice of active consumers to be switched off for the current hour is optimized if the amount of electricity is not enough, even taking into account a decrease in its consumption. The developed methodology is based on the corresponding mathematical models at each of their stages, for which the corresponding optimization problems were formulated at each stage. Examples of solving problems by exact and approximate methods are given. The developed models are recommended to the regional aggregator of DR for use in the corresponding online software for balancing the demand and supply for electricity.

Another solution in the event of a shortage of electricity is to temporarily disconnect all or part of the active customers (AC) in accordance with the contractual terms with the electricity suppliers. In world practice, the main solution for involving consumers of the retail electricity market in DM was the creation of specialized organizations – demand management aggregators (ADM), whose commercial activity is to provide demand response services. It is important in

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[262] Ribó-Pérez, D., Larrosa-López, L., Pecondón-Tricas, D., Alcázar-Ortega, M. 2021. A Critical Review of Demand Response Products as Resource for Ancillary Services: International Experience and Policy Recommendations. Energies, 14, 846. https:// doi.org/10.3390/en14040846

IT ADM to use the appropriate analytical tools, on the basis of which it would be possible to carry out optimization calculations to determine both the amount of purchased electricity and temporarily disconnected AC. Thus, we get two optimization problems:

1) optimization of the volume of reducing the consumption of electricity in case of its shortage;
2) determination (scheduling) of temporarily disconnected user groups in the event of a shortage of electricity.

To solve the problem, it is necessary to develop appropriate mathematical models and methods for their application, which are applied on the basis of forecast information on the amount of electricity shortage and its cost upon purchase.

The present research is devoted to the development of appropriate DR models and their validation, which, with this approach, can be considered pioneering in the area under consideration.

Stages of solving the problems of optimal regulation of the balance of supply and demand of consumed energy

The average daily generation and consumption of electricity, depending on many factors, in Latvia, as in many other EU countries, is generally not balanced, therefore Latvia carries out both imports and exports of electricity, buying and selling it on the NordPool electricity exchange. The sale and purchase of electricity is carried out by bid – one-time applications per day to the exchange for tomorrow before the start of trading, which determines the amount in megawatt-hours (MWh) that is missing for energy consumption. The price of one MWh of traded electricity is determined by the exchange. It is proposed to solve the optimization problems of operational-hour energy consumption in case of its potential shortage in two stages (see Figure 4.6). At the first stage, based on the data on the forecast of energy shortages, the amount of additional purchased electricity for tomorrow is optimized. Forecast data are always probabilistic, therefore it is quite plausible to assume that even with the additional purchase of energy, completed yesterday, it may not be enough at certain hours of the current day and additional purchase on this day is no longer possible. Therefore, it is necessary to solve the problem of the second stage – optimization of the number, type and regional location of the hourly AC shutdown. Note that the first task is solved for the entire region (country), based on energy consumption per day, and the second task – for each current hour of energy shortage.

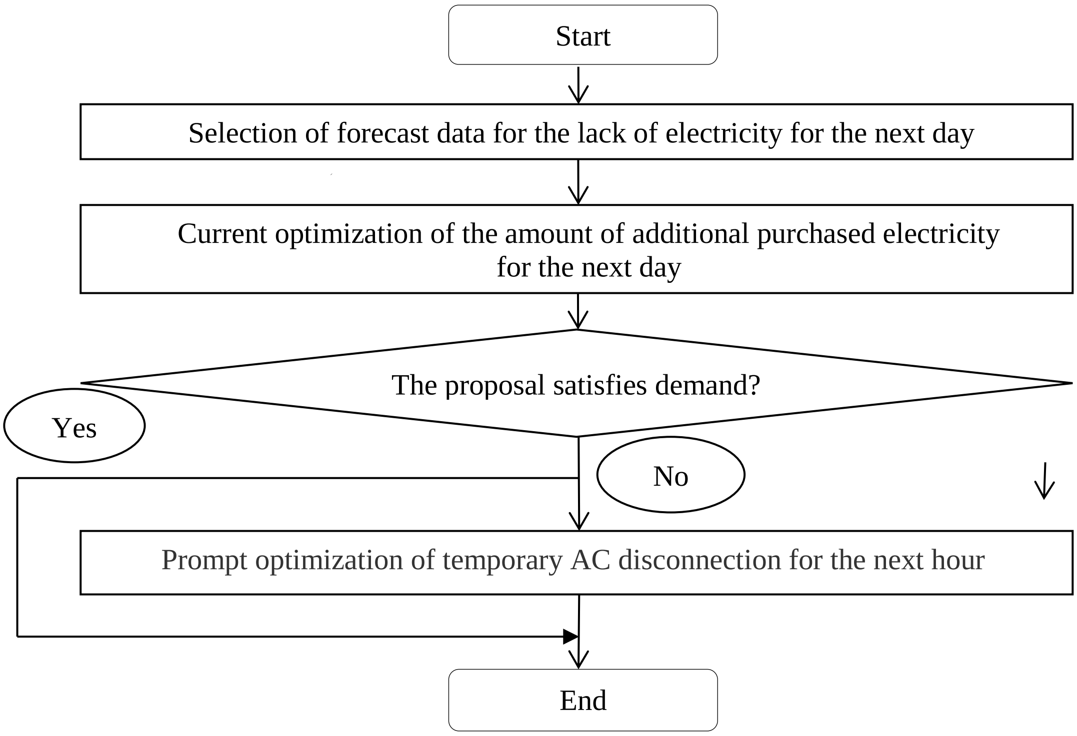

Figure. 4.6 **The algorithm structure of the two-stage procedure for optimal regulation of the balance of supply and demand for consumed electricity for the next day**

Source: created by the author

a. The problem of the current optimization of the amount of additional purchased electricity for the day ahead with the forecast of its shortage

According to statistics (see Chapter 1), the excess of imports over exports of electricity in Latvia, i.e. its shortage averaged 1118 MWh in 2019 and about 3.06 MWh per day, which is about 18 % of the annual consumption of 6108 MWh. In general, the import was 4612 MWh and about 12.6 MWh per day. Current purchase prices *(c)* for 1 MWh ranged from 1 to 487 (EURO / MWH) and averaged $\hat{c}$ = 155.6 EURO / MWh. At the same time, the selling price of electricity (z) for various types of consumers in Latvia (households, agriculture, industrial enterprises, etc.) is always constant throughout the day and averages $\hat{z}$ EURO / MWh. Thus, the purchase of the missing electricity on the exchange is in all cases beneficial if $\hat{z} \geq c$ and the total purchase price *C (i) i* MWh (i = 1, 2, ..., n) linearly depends on *c*, i.e. *C (i = ic)*, where c is the predicted value of the price of 1 MWh on the exchange for the next day. If *C (i)* depends nonlinearly on *c*, the value of *C (i)* with an increase in i may turn out to be too large. Therefore, in such cases, it is proposed to optimize the volume *(i)* of electricity purchased at the exchange, taking as a criterion the inequality:

$$Q = max \sum_{i=1}^{n} [i\hat{z} - C(i,c)] \le 0 \qquad (4.2.)$$

i – predicted amount of MWh power shortages for the next day;

$\hat{z}$ – the average price of 1 MWh of electricity supplied to consumers in Latvia (on the domestic market, the price of electricity does not change during the day);

$i\hat{z}$ – the cost of selling additional electricity purchased to Latvian consumers i MWh on the exchange;

c – predicted price of 1 MWh next day on the exchange;

C(i,c) – nonlinear function of the cost of additionally purchased electricity i MWh at the price c on the NordPool exchange in the Latvian trade zone.

Thus, it is advisable to purchase only those i MWh of electricity for which the inequality max $Q \le 0$ is satisfied. In any case, the decision on additional purchase remains with the Aggregator, which makes a decision not only on the basis of economic, but also other considerations.

Case study

The formulated optimization problem (4.2) is quite simple. Let us give its solution using an example based on the following considerations:

1. According to statistics (see Chapter 1), the excess of imports over exports of electricity in Latvia, i.e. its shortage averaged 1118 MWh in 2019 and about 3.06 MWh per day. Therefore, the approximate value of the index n is no more than 10 MWh.
2. The price $\hat{z}$ is assumed constant and equal to 150 EURO / MWH, based on the price of 0.15 EURO per 1 kilowatt hour.
3. The price of one MWh s on the exchange may vary widely. In particular, according to (Annex I Table 1 2015-2019 Wind / price statistic hour) for the period from 01.01 to 20.08 2019, this price varied from one to 484 EURO / MWh. For example, the dependence C(i,c) = $c^{i/2}$ is chosen with an initial c = 5 EURO / MWh.

The calculated data of the example and the result obtained are shown in Table 4.15.

Table 4.15

The problem of the current optimization of the amount of additional purchased electricity for the day ahead with the forecast of its shortage (1)

I	$i\hat{z}$	***C(i,c)***	***Q***
1	150	3.2	146.8
2	300	10	290
3	450	31.6	418.4
4	600	100	500
5	750	316.2	433.8
6	900	1000	(-)100

Source: created by the author

The graphs of the dependences $i\hat{z}$ and *C (i, c)* are shown in Figure 4.6

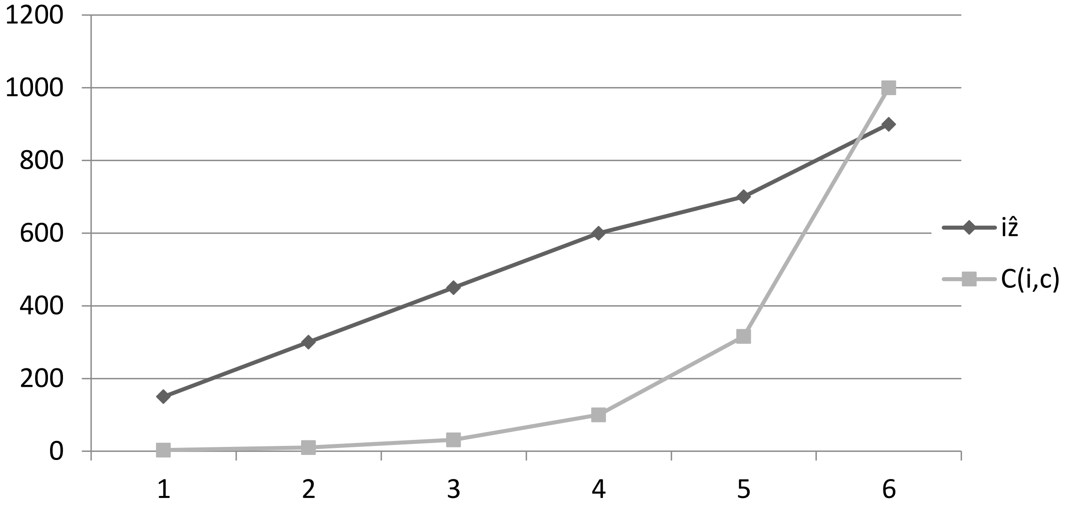

Figure 4.6 **The problem of the current optimization of the amount of additional purchased electricity for the day ahead with the forecast of its shortage**

Source: created by the author

The calculation example shows that with the given initial data, the purchase of 6 MWh on the exchange is not profitable, since the *Q* criterion takes on a negative value (*Q* = -100). A reliable assessment of the functional dependence C (i, c) is important in the practical application of this problem. With a linear dependence C (*i, c*), the formulation of the problem in the form (1) does not make sense, since for any *n* the inequalities $Q > 0$ or $Q < 0$ will be satisfied, depending on the relation $\hat{z}$ and *c*.

b. The task of operational optimization of disconnected AC groups for the next hour in case of a power shortage

In case, if consumer would like to maintain a certain consumption habits during peak hours and not change consumption behaviour, then they are ready to pay for it. However, if active consumers decide to not exceed budget / get profit, then they should alter energy consumption and turn off some appliances / equipment and shift the consumption to off-peak hours.

Combinatorial Optimization Methodology: Knapsack Problem

The knapsack problem (KP) is a very simple non-trivial integer programming model with binary variables and is a classic form of a maximization problem, which has been studied for centuries. Although this method has only one single constraint and positive coefficient, this simple program is considered difficult problem. This problem has borrowed its name by considering a mountaineer who has decided to pack his knapsack (rucksack) to climb a mountain. The capacity of his knapsack is limited, so he needs to select items carefully according to their values and weight.[263]

An important task with the current shortage of electricity is the choice of a mathematical model for its distribution between consumers of various groups and regions where such groups are represented, and the determination of the amount of disconnected electricity in each of the groups. Of course, such models constitute a trade secret of the Aggregator regulating the balance of demand and consumption of electricity, and, as a rule, are not published. One of the approaches to formulating such a problem can be reduced to the problem of integer optimization " Knapsack Problem", the purpose of which is to select a subset of items with the maximum total cost from a given set of items with the properties "cost" and "weight", while observing the constraint on the total weight[264]. There are different variations of this task for different objects. In particular, in the works [265], [266] modifications of this problem are used in application to the tourism industry.

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[263] Sianaki, O.A. 2015. Intelligent Decision Support System for Energy Management in Demand Response Programs and Residential and Industrial Sectors of the Smart Grid.[Accessed 05.07.21]

[264] Martelo, S., Toth, P. 1990. Knapsack problems. B – Great Britain: Wiley, 306 c. ISBN 0-471-92420-2. [Accessed 05.07.21]

[265] Rebezova, M. 2013. A Modification of the Knapsack Problem Taking Into Account the Effect of the Interaction Between the Items. Automatic Control and Computer Sciences, Vol. 47, № 2, Allerton Press, Inc. 107–112. ISSN 0146-4116. [Accessed 05.07.21]

[266] Mahareva, K. 2019. Concept of creation and analysis of competitiveness regional NDC-aggregator company. Vestnik Cankt-Peterburgskogo Universiteta Grazdanskoj Aviacii. (In Russian language). № 1(22). [Accessed 05.07.21]

In general, to maximize the total profit, the binary KP can be formulated as linear integer programming as follows: find a set of Booleans $X=\{x_j\}$, such that

$$\boldsymbol{F = max \sum_{j=1}^{m} w_j z_j} \tag{4.3.}$$

$$\boldsymbol{\sum_{j=1}^{m} w_j x_j \leq W} \tag{4.4.}$$

j – a group of active customers with the same tariff plan (households, industry, agriculture, transport, business, etc.) in the corresponding territorial unit (city, district, rural municipality, etc.);

$x_j = 1$, if the consumer group j does not turn off for electricity consumption at the current hour (the group is “placed in the knapsack”) and $x_j = 0$ – otherwise (disconnects from electricity consumption at the current hour (the group “does not fit in the knapsack”);

w_j – the amount MWh of electricity consumed at the corresponding hour for a group of consumers j;

z_j – electricity market price (€ / MWh) for the respective consumer group;

m – the maximum number of consumer groups with different tariff plans (different tariffs per unit of electricity);

W – the amount MWh of electricity distributed in the current hour for all consumer groups.

The electricity market where the model is used is assumed to be organized according to the day-ahead trading rules as they are implemented in the Elspot market of the Nord Pool (NP) power exchange, which is one of the largest electrical power exchanges in Europe. The set task makes sense if the current demand for electricity exceeds its supply. The solution to the problem is to iterate over the options and find the option with the maximum value among those whose total electricity consumption does not exceed its supply.

Of course, it is necessary to exclude enterprises with a continuous technological cycle of production from the number of disconnected groups of enterprises, the medical institutions, emergency services, traffic lights, electricity producers and other consumers who are not active customers and the disconnection of which may lead to negative consequences. Therefore, the proposal should not include such consumer groups.

The KP problem is solved by various methods. There are various forms of KPs such as binary, the bounded, unbounded, multiple, multiple-choice, quadratic, multi-objective, precedence constraint, nonlinear, fractional, on-line, and semi online knapsack problems. Furthermore, there are various methodologies for solving KP such as the greedy algorithm, linear programming relaxation, dynamic programming, branch and bound, and approximation algorithms. When choosing a method, it is necessary to choose between exact methods, which are not applicable for “knapsacks” of large dimensions, and approximate – heuristic, which work quickly, but do not provide an optimal solution. The choice of one method or another depends mainly on the dimension of the problem, determined by the number of enumeration of various options, which in turn are determined by the amount of initial data. If the amount of initial data leads to an enumeration of thousands and tens of thousands of options, then exact methods are used, such as the exhaustive search method, the branch-and-bound method, and the dynamic programming method. If the accuracy of the solution does not play a big role, or the amount of input data leads to hundreds of thousands or more options when enumerating, in which none of the exact methods is workable, then approximate algorithms are used to solve the problem. All algorithms, except for full enumeration, pre-sort the initial data according to the specified criteria, and then iteratively enumerate the options left after sorting.

The simplest exact method is the exhaustive search method[267]. However, this method is the most computationally intensive. The complexity of the problem being solved (the number of options to be sorted out) will be $O(2^m)$ (O – coefficient characterizing the number of computational operations to compute one option). This method is used for values of m that allow obtaining a solution in the foreseeable processor time. For example, if there are $m = 20$ consumer groups (the dimension of the problem will be $O(2^{20}) = 1048576$ and the frequency of the laptop is 3 × 109, the problem is solved in just a few seconds. But for significantly large values of m, computer calculations can take tens of minutes and hours, during which waiting for the final result is tedious and unacceptable for a researcher.

Exact methods also include better enumeration methods – the branch and bound method, and the dynamic programming method.

The branch and bound method[268] is a variation of the brute force method with the difference that the brute force excludes non-optimal brute force branches. According to one of the possible algorithms, in the process of building a tree for each node, the upper bound for the value of the solution is estimated, and then the construction of the tree continues only for the node with the maximum value estimate. The complexity of this method $O(^{2m}/2m)$. The ability of the branch and bound method to reduce the number of iterations is heavily based on the input data. This method is effectively applied only if the specific values of items differ significantly.

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[267] Martello, S., Toth P. 1990. Knapsack problems: algorithms and computer implementations. John Wiley & Sons Ltd. C. 29,50. 296 c. ISBN 0-471-92420-2

[268] Reeves, C.R. 1993. Modern Heuristic Techniques for Combinatorial Problems. Oxford: Blackwell Scientific Publications.

Otherwise, the complexity of the branch-and-bound method approaches the complexity of the exhaustive search method, i.e. O($^{2m}/2m$) → O(2^m).

The solution of the problem by the method of dynamic programming is that the optimal solution at a certain step is found on the basis of the previously found optimal solutions at the previous steps. Thus, in order to find the optimal solution in the last stage, it is necessary to optimize all the solutions in the previous stages. The complexity of the computational algorithm of the method is O(mW). Any solution to Boolean problems in the formulation (3.3, 3.4) implies an enumeration of options, the number of which qualitatively increases with an increase in their dimension.

In order to save computational time, heuristic algorithms are used that give suboptimal results, i.e. close to optimal, but do not guarantee optimal results. Approximate algorithms include, in particular, “greedy”, genetic, and other similar algorithms. Solving the problem with a “greedy” algorithm involves sorting items according to their specific value (that is, the ratio of the value of an item to its weight) and placing items with the highest specific value in the backpack by going through the sorted options [269]. The difficulty of sorting items is O($m\log(m)$).

Genetic Algorithm [270] handles many of the best solutions to date. Many of these decisions are called generation. After a series of generational changes in which the fittest individuals are crossed and the remaining individuals are ignored, the algorithm is supposed to improve the original solutions.

Currently, many software packages and online calculators have been developed, which provide the solution of the problem “About the Knapsack” with accurate and heuristic methods. Therefore, it is not advisable to develop your own software. It is enough only to qualitatively and quantitatively determine the initial data that determine the complexity of solving the problem, and, in accordance with the estimated complexity, choose the necessary tools.

The validation of optimization mathematical model of disconnected AC groups for the next hour in case of a power shortage is done by author. To check the model operability, the model validation is carried out on an abstract numerical example, in which: W – the amount MWh of electricity distributed in the current hour for all consumer groups; j – a group of active customers with the same tariff plan (households, industry, agriculture, transport, business, etc.) in the corresponding territorial unit (city, district, rural municipality, etc.);

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[269] Martello, S., Toth P. 1990. Knapsack problems: algorithms and computer implementations. John Wiley & Sons Ltd., C. 29,50. 296 c. ISBN 0-471-92420-2]

[270] Davis, I. (ed.) 1991. Handbook of Genetic Algorithms. New York: Van Nostrand Reinhold.

Let us consider the exact and heuristic methods for solving the required problem using examples of the exhaustive search method and the “greedy” method for W = 10 (MWh) and other initial data presented in table. 4.16.

To solve the problem, taking into account all conditions, to verify and validate the result, the Mathcad software is employed, implementing the search of all possible solutions of the problem in Equation (4.3), with the restrictions and conditions (4.4), gives the maximum profit F at a different value of the price z.

Table.4.16

An example of initial data for solving a problem in the formulation (4.3; 4.4)

j	w_j **(MWh)**	z_j **(EURO)**	F
1	5	120	480
2	4	130	520
3	3	250	750
4	1	300	300

Source: created by the author

From the data table. 4.16 it follows that the demand for electricity consumption in the current hour exceeds consumption ($\sum_{j=1}^{m} w_j$ = 13, > 10). Consequently, it is necessary to solve the optimization problem of choosing the AC group (s), which must be temporally disconnected from electricity consumption.

Table 4.17 displays all possible combinations of the values of the variables xj, the corresponding sets of groups and the values of the criterion F for solving the problem by the exhaustive search method. Sets of non-disconnectable AC groups can be either each group separately (which is clearly not optimal), or other combinations of 2 or 3 groups, in which the total demand for electricity ($\sum_{j=1}^{m} w_j \leq 10$. If a group consists of only one consumer or a combination of groups consumes > 10 MWh of electricity, then the calculated data for it in table 4.17 not shown (–).

Table 4.17

An example of solving the problem in the formulation (4.1, 4.2)

x_1	x_2	x_3	x_4	**Set of** x_j	$\sum_{j=1}^{m} w_j$	F
0	0	0	0	{0}	–	–
0	0	0	1	{4}	–	–
0	0	1	0	{3}	–	–
0	0	1	1	{3, 4}	4	1050

Table 4.17 continued

x_1	x_2	x_3	x_4	**Set of x_j**	$\sum_{j=1}^{m} w_j$	F
0	1	0	0	{2}	–	–
0	1	0	1	{2, 4}	5	820
0	1	1	0	{2, 3}	7	1270
0	1	1	1	{2, 3, 4}	8	1570
1	0	0	0	{1}	–	–
1	0	0	1	{1, 4}	6	780
1	0	1	0	{1, 3}	6	1230
1	0	1	1	{1, 3, 4}	9	1530
1	1	0	0	{1, 2}	9	1000
1	1	0	1	{1, 2, 4}	10	1300
1	1	1	0	{1, 2, 3}	–	–
1	1	1	1	{1, 2, 3, 4}	–	–

Source: created by the author

Zero in the matrices mean that there are no corresponding options for this group of customers. From the calculated data it follows that the maximum value of the criterion profit F = 1570 in case of meeting the electricity demand for the current hour will be for groups {2, 3, 4} and the group will be switched off {1}.

The specific value of consumer groups (from table. 4.16) is presented in table. 3.18 for the subsequent solution of the problem in the formulation (4.3, 4.4) by the “greedy” method.

Table 4.18

Specific consumer value data for the example under consideration

J	**1**	**2**	**3**	**4**
z_j / w_j	24	32.5	83.3	300

Source: created by the author

Of the permissible combinations of groups for which it is possible to meet the demand for electricity, we single out the combinations {1, 2, 4}, {1, 3, 4}, {2, 3, 4}, the total specific value of which is presented in Table. 4.19.

Table 4.19

Specific consumer value data for the example under consideration

Sets of groups	**{1, 2, 4}**	**{1, 3, 4}**	**{2, 3, 4}**
z_j / w_j	356.5	407.3	415.8

Source: created by the author

Here, too, the group for switch off will be group {1}, since the maximum unit value (415.8) will be in case the demand for the combination groups {2, 3, 4} is satisfied. In the given example, the solution of the problem by the exact method (exhaustive search) and the approximate method ("greedy" method) coincides. This coincidence is quite possible for a small number of AC groups. In practice, the number of AC groups can be measured in tens and hundreds, since, for example, different households with different tariff plans for electricity consumption can be divided into dozens of different groups, etc. Therefore, a regional aggregator should have application packages or online calculators for solving the problem in the formulation (3.3, 3.4) by both exact and approximate methods, the easiest to use are the brute force search method and the greedy method, taking into account the complexity of the problem.

Conclusions

1. Latvia suffers from a shortage of electricity for about 18 % of annual consumption, therefore, the problem of regulating the balance of demand and supply of consumers for its consumption is the most important task of the Aggregator, for the solution of which the author proposes a two-stage optimization procedure as the amount of electricity purchased for the next day on the NordPool exchange in the Latvian trade zone and the choice of groups to be switched off by the AC in case of shortage during the current hours of its consumption. For each stage, the formulation of the problem is developed and methods for their solution with deterministic initial data are considered. Further development of the developed methodology in the future is supposed to be carried out with random initial data.
2. In the given example, the solution of the problem by the exact method (exhaustive search) and the approximate method ("greedy" method) coincides. This coincidence is quite possible for a small number of AC groups. In practice, the number of AC groups can be measured in tens and hundreds, since, for example, different households with different tariff plans for electricity consumption can be divided into dozens of different groups, etc. Therefore, a regional aggregator should have application packages or online calculators for solving the problem in the formulation (4.3, 4.4) by both exact and approximate methods, the easiest to use are the brute force search method and the greedy method, taking into account the complexity of the problem.

3. The level of awareness prosumerism of the respondents who participated in the survey is relatively high. Although, the author suggests that those who are not familiar with the term prosumerism simply did not continue to fill out the questionnaire.

It is important to note that the behaviour of electricity consumers testifies to the great potential of Latvian consumers to participate in the electricity generation and sale market. This means the potential to participate in the aggregation of electricity demand.

Based on the analysis the main **recommendations for the development of Regional electricity Aggregator in Latvia** as follow:

1. A regional electricity aggregator should have application packages or online calculators for solving the problem by both exact and approximate methods, the easiest to use are the brute force search method and the greedy method, taking into account the complexity of the problem
2. Expanding the proposed knapsack method to an online stochastic knapsack: in Chapter 4proposed optimization methodology, because there the data input to the system is done within the offline state. But the online and stochastic method can provide an approximation of future energy consumption trends for the Regional Aggregator.
3. The author of the Thesis proposes the implementation in Latvia of an expanded intelligent system (IS) in order to create a unique energy consumption profile for family members: comparing an electrical system with a telecommunications and multimedia system, especially a mobile network, users of this system receive data on their consumption in real time. In addition, mobile network providers can inform their users of any over-consumption trend and offer them more suitable services based on the user's consumption profile. To add such intelligence to the smart grid, the proposed intelligent decision support system must be able to study the consumer behaviour and lifestyles of users.

Conclusions and Recommendations

The development of energy industry and its segments including renewable energy sources penetration and impact, the role and place of market electricity price for all categories of consumers and economy of Latvia as whole is a top priority governmental task. It is reflected in the main guidelines and official policy documents of the Saeima of the Republic of Latvia, the Cabinet of Ministers, the Ministry of Economy and other ministries and departments with the result-based consistent monitoring at the state level, and of course on the EU level. These documents set goals, determine strategies and activities for the transformation of industry. Nevertheless, there is almost no attention paid to the development of IT technologies with the goal to regulate demand side of electricity.

Therefore, the relevance of the Thesis research is confirmed by the author's design of the concept for the development electricity demand side services in Latvia on the basics of the Regional Aggregator.

According to the results of the research, the following main conclusion have been formulated:

1. Having analysed the theoretical framework, the genesis of scientific research of the Demand Response, the Author suggested the approaches of the improvement of definitions and classifications of the electricity consumption response. The electricity Demand Response 's classification and its chronology has been developed. On the grounds of the genesis in the field of demand management for electricity consumption were proposed, systematized, and substantiated the stages of scientific research on the subject.
2. The analysis and systematisation of its stages allows to conclude that the development of scientific research is influenced by both external factors related to electricity, such as economic crises, the spread of information technologies, and internal factors, such as the development of energy markets, the development of distributed and renewable energy technologies, the emergence of new technological trends.
3. The author proposes combinatorial optimization for implementation of the concept of regional Demand Response Aggregator, that will allow to solve the problem of reducing electricity consumption and, at the second stage, the choice of active consumers to be switched off for the current hour is optimized if the amount of electricity is not enough, even taking into account a decrease in its consumption.

4. As a result of the assessment of various legal documents and regulations suggested by international organisations such as UN, EU as well as the Cabinet of Ministries of the Republic of Latvia, the author concludes, that the more liberalized the market is, the more it responds to fluctuations in demand and supply. In an effort to maximize the liberalization of the European energy market, European market decision makers intended to use it as a tool that would provide an ever-increasing, growing, and diversified range of offers, which would put downward pressure on prices.
5. Until recently, the Baltic countries have not used all the potential, which in combination with the EU target of carbon neutral by 2050, investments, support schemes and auctions, smart strategy and implementation can lead us to sharply increasing RES, especially of wind and solar capacities. According to Latvia's National Energy and Climate Plan 2021–2030, the Latvian electricity transmission system can accept up to 800 MW of additional capacity from new RE plants, which is about a third of all electrical capacities currently installed in Latvia.
6. In developed of a methodology for statistical analysis of wind energy yearly and monthly (2019) data, it was established that for practical use should be applied analysis methods that give not only good quality criteria, but also the values of the considered indicators corresponding to the logical meaning. Multiple (polynomial) regression has proven to be an effective tool for electricity demand forecasting. One of its main strengths is the negligible computational time it takes to perform forecasts without losing much in terms of accuracy. Furthermore, the forecasting model can be improved by certain modifications, the most promising of which has turned out to be subtraction of the model residuals averaged over hour-of-day.
7. During the peak wind power and peaks of electricity price, multiple (polynomial) regression has proven to be an ineffective tool for the analysis of monthly statistical data gave unsatisfactory results, therefore, it is recommended to use the model of sinusoidal dependence of the corresponding indicators on the month number.
8. While other modifications (x component and time series filtration) did not produce a consistently beneficial effect over the whole dataset, there were days when their inclusion aided in improving the accuracy. Thus, a model, which automatically selects the features the forecasting program, should consider before each daily forecast is advisable. Additionally, it should consider automatic selection of the training set size, since the optimum look-back horizon tends to vary during the peak wind power.

9. Trends in the production, consumption and export of electricity in Latvia are weak, but upward. The trends in imports and the excess of imports over exports of electricity are of a downward nature, which indicates the dynamics of a slow but decreasing dependence of Latvia on imports of electricity. Cannot be used for a short-term “approximate” forecast of this indicator.
10. The trend of planned wind power consumption for the day ahead in Latvia has a clearly pronounced upward character with a high strength of connection with statistical data (coefficient R2 = 0.7) and indicates a steady annual increase in wind power consumption in Latvia, which corresponds to the goals of increasing the share of RES in final energy consumption should grow and reach its share up to 45 % by 2030. At the same time, the upward trend in the cost of one MWh (wind power consumed in Latvia with a high value of R2 = 0.7) does not correlate with the trend in its consumption. This circumstance, as well as the consequences of the coronavirus pandemic, may require adjusting plans to increase electricity consumption from RES, which will require a more detailed assessment of the volume of wind power imports and, possibly, the implementation of measures to increase the capacity for the production of this energy in Latvia.
11. There has been set the task and offered improved economic and mathematical model of optimization of regional electricity aggregator, focused on reduction costs of the PP and electricity consumers. Research reveals that there is no such service in Latvia. Although, institutionally everything is ready, technologically it is necessary to develop electricity smart grid and install smart meters. The method of solving the optimization problem was tested on validation case studies with software *Mathcad* and demonstrated its appropriateness and effectiveness.
12. Latvia suffers from a shortage of electricity for about 18 % of annual consumption, therefore, the problem of regulating the balance of demand and supply of consumers for its consumption is the most important task of the Aggregator, for the solution of which the author has proposed a two-stage optimization procedure as the amount of electricity purchased for the next day on the NordPool exchange in the Latvian trade zone and the choice of groups to be switched off by the AC in case of shortage during the current hours of its consumption. For each stage, the formulation of the problem is developed and methods for their solution with deterministic initial data are considered. Further development of the developed methodology in the future is supposed to be carried out with random initial data.

13. In the given case study, the KP solution of the problem by the exact method (exhaustive search) and the approximate method (“greedy” method) coincides. This coincidence is quite possible for a small number of AC groups. In practice, the number of AC groups can be measured in tens and hundreds, since, for example, different households with different tariff plans for electricity consumption can be divided into dozens of different groups, etc. Therefore, a regional aggregator should have application packages or online calculators for solving the problem in the formulation (3.3, 3.4) by both exact and approximate methods, the easiest to use are the brute force search method and the greedy method, taking into account the complexity of the problem.
14. The level of awareness prosumerism of the respondents who participated in the survey is relatively high. Although, the author suggests that those who are not familiar with the term prosumerism simply did not continue to fill out the questionnaire.

It is important to note that the behaviour of electricity consumers testifies to the great potential of Latvian consumers to participate in the electricity generation and sale market. That means the potential to participate in the aggregation of electricity demand.

Therefore, the hypothesis put forward by author is proved, the goal and objectives are fulfilled.

Recommendations

Based on the conclusions made during the work the following suggestions were formulated by the author for the Government structures of Latvia, universities of Latvia and enterprises.

To the Ministry of Economy of Republic of Latvia.

It is suggested to designate the priority of the development of the smart grid in Latvia and to finalize to provision of households with smart meters. That allows after 2025 promptly involve electricity consumers to the demand response aggregation.

The implementation in Latvia of an expanded intelligent system (IS) in order to create a unique energy consumption profile for family members: comparing an electrical system with a telecommunications and multimedia system, especially a mobile network, users of this system receive data on their consumption in real time. In addition, mobile network providers can inform their users of any over-consumption trend and offer them more suitable services based on the user's consumption profile. To add such intelligence to the smart grid, the proposed intelligent decision support system must be able to study the consumer behaviour and lifestyles of users.

To the Ministry of Education of the Republic of Latvia.

Acknowledging, there some pretty qualitative study programmes on sustainable development in economics, business, environment, and psychology education in Latvia, the author recommends to develop and include concept of “electricity prosumerism” to both secondary and higher education.

To the Central Statistical Bureau of Republic of Latvia.

To recognize the topicality of transitional processes of CEEP in the Latvia and to specify the definition of prosumerim and active consumer in energy sector, by the including of the system of evaluation of the interaction between: consumed electricity and average bill for prosumers households. It will ensure opportunity to study the consumer behaviour and lifestyles of users.

To the enterprises, which plan to offer electricity Demand Response services in Latvia.

For companies planning to offer electricity PR services in Latvia: extending the proposed “knapsack” method to a stochastic one can provide a rough approximation of future energy consumption trends for a regional aggregator.

Publications and Reports on the Thesis topic

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3. Silinevicha, V. 10.12.2020. XXIII. ročníku mezinárodní odborné konference DANĚ – TEORIE A PRAXE. Political, Economic, Social and Technological Perspectives of Aggregator of Demand Response for Renewable Integration, Brno, Czech Republic.
4. Silinevicha, V. 14–15.11.2019. VI International Conference Geopolitical aspect of relations: Russia-West, Wind power influence to wholesale energy prices in Latvia, Humanities University in Siedlce, Poland. (Baltic International Academy).

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Appendices

Appendix 1

Relationships between physical parameters and real-time price variables modelling input data and sources in August 2019

Number	Time	Wind MWh	Price, euro
1	01.08.2019 00:00 – 01.08.2019 01:00 (CET)	20	39
2	01.08.2019 01:00 – 01.08.2019 02:00 (CET)	15	37.98
3	01.08.2019 02:00 – 01.08.2019 03:00 (CET)	12	37.44
4	01.08.2019 03:00 – 01.08.2019 04:00 (CET)	10	37.26
5	01.08.2019 04:00 – 01.08.2019 05:00 (CET)	8	37.37
6	01.08.2019 05:00 – 01.08.2019 06:00 (CET)	6	42.1
7	01.08.2019 06:00 – 01.08.2019 07:00 (CET)	4	62.38
8	01.08.2019 07:00 – 01.08.2019 08:00 (CET)	2	66.86
9	01.08.2019 08:00 – 01.08.2019 09:00 (CET)	2	68.59
10	01.08.2019 09:00 – 01.08.2019 10:00 (CET)	3	69.82
11	01.08.2019 10:00 – 01.08.2019 11:00 (CET)	4	69.85
12	01.08.2019 11:00 – 01.08.2019 12:00 (CET)	7	69.74
13	01.08.2019 12:00 – 01.08.2019 13:00 (CET)	9	69.9
14	01.08.2019 13:00 – 01.08.2019 14:00 (CET)	13	69.8
15	01.08.2019 14:00 – 01.08.2019 15:00 (CET)	16	69.75
16	01.08.2019 15:00 – 01.08.2019 16:00 (CET)	20	69.8
17	01.08.2019 16:00 – 01.08.2019 17:00 (CET)	25	63.69
18	01.08.2019 17:00 – 01.08.2019 18:00 (CET)	30	60.31
19	01.08.2019 18:00 – 01.08.2019 19:00 (CET)	32	67.42
20	01.08.2019 19:00 – 01.08.2019 20:00 (CET)	33	63.38
21	01.08.2019 20:00 – 01.08.2019 21:00 (CET)	33	66.43
22	01.08.2019 21:00 – 01.08.2019 22:00 (CET)	33	57.94
23	01.08.2019 22:00 – 01.08.2019 23:00 (CET)	31	40.09
24	01.08.2019 23:00 – 02.08.2019 00:00 (CET)	25	39.61
25	02.08.2019 00:00 – 02.08.2019 01:00 (CET)	21	39.04
26	02.08.2019 01:00 – 02.08.2019 02:00 (CET)	22	38.89
27	02.08.2019 02:00 – 02.08.2019 03:00 (CET)	23	38.2
28	02.08.2019 03:00 – 02.08.2019 04:00 (CET)	23	37.93
29	02.08.2019 04:00 – 02.08.2019 05:00 (CET)	23	38.1
30	02.08.2019 05:00 – 02.08.2019 06:00 (CET)	23	52.55
31	02.08.2019 06:00 – 02.08.2019 07:00 (CET)	21	59.49
32	02.08.2019 07:00 – 02.08.2019 08:00 (CET)	19	63.46
33	02.08.2019 08:00 – 02.08.2019 09:00 (CET)	18	65.83
34	02.08.2019 09:00 – 02.08.2019 10:00 (CET)	20	65.46
35	02.08.2019 10:00 – 02.08.2019 11:00 (CET)	22	64.74
36	02.08.2019 11:00 – 02.08.2019 12:00 (CET)	28	65.32
37	02.08.2019 12:00 – 02.08.2019 13:00 (CET)	31	66.9
38	02.08.2019 13:00 – 02.08.2019 14:00 (CET)	36	65.66
39	02.08.2019 14:00 – 02.08.2019 15:00 (CET)	47	63.76
40	02.08.2019 15:00 – 02.08.2019 16:00 (CET)	47	63.08

Appendix 1 continued

Number	Time	Wind MWh	Price, euro
41	02.08.2019 16:00 – 02.08.2019 17:00 (CET)	48	67.61
42	02.08.2019 17:00 – 02.08.2019 18:00 (CET)	48	67.67
43	02.08.2019 18:00 – 02.08.2019 19:00 (CET)	45	66.26
44	02.08.2019 19:00 – 02.08.2019 20:00 (CET)	47	66.69
45	02.08.2019 20:00 – 02.08.2019 21:00 (CET)	47	47.82
46	02.08.2019 21:00 – 02.08.2019 22:00 (CET)	46	41.58
47	02.08.2019 22:00 – 02.08.2019 23:00 (CET)	48	40.76
48	02.08.2019 23:00 – 03.08.2019 00:00 (CET)	47	39.98
49	03.08.2019 00:00 – 03.08.2019 01:00 (CET)	45	38.96
50	03.08.2019 01:00 – 03.08.2019 02:00 (CET)	51	38.16
51	03.08.2019 02:00 – 03.08.2019 03:00 (CET)	52	38.05
52	03.08.2019 03:00 – 03.08.2019 04:00 (CET)	54	37.74
53	03.08.2019 04:00 – 03.08.2019 05:00 (CET)	55	37.66
54	03.08.2019 05:00 – 03.08.2019 06:00 (CET)	37	37.87
55	03.08.2019 06:00 – 03.08.2019 07:00 (CET)	22	38.11
56	03.08.2019 07:00 – 03.08.2019 08:00 (CET)	12	38.41
57	03.08.2019 08:00 – 03.08.2019 09:00 (CET)	10	38.97
58	03.08.2019 09:00 – 03.08.2019 10:00 (CET)	16	46.43
59	03.08.2019 10:00 – 03.08.2019 11:00 (CET)	23	43.16
60	03.08.2019 11:00 – 03.08.2019 12:00 (CET)	36	43.19
61	03.08.2019 12:00 – 03.08.2019 13:00 (CET)	61	43.17
62	03.08.2019 13:00 – 03.08.2019 14:00 (CET)	82	39.14
63	03.08.2019 14:00 – 03.08.2019 15:00 (CET)	102	38.95
64	03.08.2019 15:00 – 03.08.2019 16:00 (CET)	111	38.91
65	03.08.2019 16:00 – 03.08.2019 17:00 (CET)	114	38.89
66	03.08.2019 17:00 – 03.08.2019 18:00 (CET)	108	38.96
67	03.08.2019 18:00 – 03.08.2019 19:00 (CET)	91	39.75
68	03.08.2019 19:00 – 03.08.2019 20:00 (CET)	76	41.08
69	03.08.2019 20:00 – 03.08.2019 21:00 (CET)	70	41.02
70	03.08.2019 21:00 – 03.08.2019 22:00 (CET)	67	40.59
71	03.08.2019 22:00 – 03.08.2019 23:00 (CET)	63	40.84
72	03.08.2019 23:00 – 04.08.2019 00:00 (CET)	56	39.47
73	04.08.2019 00:00 – 04.08.2019 01:00 (CET)	50	38.93
74	04.08.2019 01:00 – 04.08.2019 02:00 (CET)	41	38.04
75	04.08.2019 02:00 – 04.08.2019 03:00 (CET)	35	37.45
76	04.08.2019 03:00 – 04.08.2019 04:00 (CET)	31	37.18
77	04.08.2019 04:00 – 04.08.2019 05:00 (CET)	30	37.06
78	04.08.2019 05:00 – 04.08.2019 06:00 (CET)	28	36.48
79	04.08.2019 06:00 – 04.08.2019 07:00 (CET)	22	37.4
80	04.08.2019 07:00 – 04.08.2019 08:00 (CET)	17	38.09
81	04.08.2019 08:00 – 04.08.2019 09:00 (CET)	15	38.69
82	04.08.2019 09:00 – 04.08.2019 10:00 (CET)	16	47.46

Appendix 1 continued

Number	Time	Wind MWh	Price, euro
83	04.08.2019 10:00 – 04.08.2019 11:00 (CET)	19	40.03
84	04.08.2019 11:00 – 04.08.2019 12:00 (CET)	27	40.02
85	04.08.2019 12:00 – 04.08.2019 13:00 (CET)	37	39.98
86	04.08.2019 13:00 – 04.08.2019 14:00 (CET)	54	39.46
87	04.08.2019 14:00 – 04.08.2019 15:00 (CET)	68	39.3
88	04.08.2019 15:00 – 04.08.2019 16:00 (CET)	86	39.2
89	04.08.2019 16:00 – 04.08.2019 17:00 (CET)	100	39.12
90	04.08.2019 17:00 – 04.08.2019 18:00 (CET)	108	39.32
91	04.08.2019 18:00 – 04.08.2019 19:00 (CET)	96	39.98
92	04.08.2019 19:00 – 04.08.2019 20:00 (CET)	87	42
93	04.08.2019 20:00 – 04.08.2019 21:00 (CET)	82	42.93
94	04.08.2019 21:00 – 04.08.2019 22:00 (CET)	78	43.42
95	04.08.2019 22:00 – 04.08.2019 23:00 (CET)	71	41.4
96	04.08.2019 23:00 – 05.08.2019 00:00 (CET)	58	40.31
97	05.08.2019 00:00 – 05.08.2019 01:00 (CET)	61	39.05
98	05.08.2019 01:00 – 05.08.2019 02:00 (CET)	45	36.89
99	05.08.2019 02:00 – 05.08.2019 03:00 (CET)	38	36.55
100	05.08.2019 03:00 – 05.08.2019 04:00 (CET)	33	36.56
101	05.08.2019 04:00 – 05.08.2019 05:00 (CET)	29	36.81
102	05.08.2019 05:00 – 05.08.2019 06:00 (CET)	22	39.33
103	05.08.2019 06:00 – 05.08.2019 07:00 (CET)	17	63.14
104	05.08.2019 07:00 – 05.08.2019 08:00 (CET)	13	64.34
105	05.08.2019 08:00 – 05.08.2019 09:00 (CET)	11	68.99
106	05.08.2019 09:00 – 05.08.2019 10:00 (CET)	12	70.2
107	05.08.2019 10:00 – 05.08.2019 11:00 (CET)	15	69.58
108	05.08.2019 11:00 – 05.08.2019 12:00 (CET)	20	66.41
109	05.08.2019 12:00 – 05.08.2019 13:00 (CET)	26	68.67
110	05.08.2019 13:00 – 05.08.2019 14:00 (CET)	31	70.22
111	05.08.2019 14:00 – 05.08.2019 15:00 (CET)	34	69.76
112	05.08.2019 15:00 – 05.08.2019 16:00 (CET)	35	67.49
113	05.08.2019 16:00 – 05.08.2019 17:00 (CET)	34	68.43
114	05.08.2019 17:00 – 05.08.2019 18:00 (CET)	32	68.47
115	05.08.2019 18:00 – 05.08.2019 19:00 (CET)	29	68.87
116	05.08.2019 19:00 – 05.08.2019 20:00 (CET)	25	69.26
117	05.08.2019 20:00 – 05.08.2019 21:00 (CET)	21	56.95
118	05.08.2019 21:00 – 05.08.2019 22:00 (CET)	17	48.24
119	05.08.2019 22:00 – 05.08.2019 23:00 (CET)	16	43.51
120	05.08.2019 23:00 – 06.08.2019 00:00 (CET)	15	39.87
121	06.08.2019 00:00 – 06.08.2019 01:00 (CET)	7	38.79
122	06.08.2019 01:00 – 06.08.2019 02:00 (CET)	11	37.83
123	06.08.2019 02:00 – 06.08.2019 03:00 (CET)	15	36.91
124	06.08.2019 03:00 – 06.08.2019 04:00 (CET)	24	36.83

Appendix 1 continued

Number	**Time**	**Wind MWh**	**Price, euro**
125	06.08.2019 04:00 – 06.08.2019 05:00 (CET)	34	36.78
126	06.08.2019 05:00 – 06.08.2019 06:00 (CET)	39	38.47
127	06.08.2019 06:00 – 06.08.2019 07:00 (CET)	35	58.96
128	06.08.2019 07:00 – 06.08.2019 08:00 (CET)	28	64.24
129	06.08.2019 08:00 – 06.08.2019 09:00 (CET)	24	67.88
130	06.08.2019 09:00 – 06.08.2019 10:00 (CET)	27	67.96
131	06.08.2019 10:00 – 06.08.2019 11:00 (CET)	31	66.54
132	06.08.2019 11:00 – 06.08.2019 12:00 (CET)	38	66.55
133	06.08.2019 12:00 – 06.08.2019 13:00 (CET)	46	68.08
134	06.08.2019 13:00 – 06.08.2019 14:00 (CET)	62	68.08
135	06.08.2019 14:00 – 06.08.2019 15:00 (CET)	76	67.7
136	06.08.2019 15:00 – 06.08.2019 16:00 (CET)	74	67.72
137	06.08.2019 16:00 – 06.08.2019 17:00 (CET)	78	66.3
138	06.08.2019 17:00 – 06.08.2019 18:00 (CET)	72	66.08
139	06.08.2019 18:00 – 06.08.2019 19:00 (CET)	61	66.44
140	06.08.2019 19:00 – 06.08.2019 20:00 (CET)	56	67.81
141	06.08.2019 20:00 – 06.08.2019 21:00 (CET)	60	49.99
142	06.08.2019 21:00 – 06.08.2019 22:00 (CET)	74	42.27
143	06.08.2019 22:00 – 06.08.2019 23:00 (CET)	92	40.81
144	06.08.2019 23:00 – 07.08.2019 00:00 (CET)	98	39.66
145	07.08.2019 00:00 – 07.08.2019 01:00 (CET)	88	38.26
146	07.08.2019 01:00 – 07.08.2019 02:00 (CET)	85	36.28
147	07.08.2019 02:00 – 07.08.2019 03:00 (CET)	80	35.76
148	07.08.2019 03:00 – 07.08.2019 04:00 (CET)	80	35.76
149	07.08.2019 04:00 – 07.08.2019 05:00 (CET)	73	35.69
150	07.08.2019 05:00 – 07.08.2019 06:00 (CET)	64	39.28
151	07.08.2019 06:00 – 07.08.2019 07:00 (CET)	54	62.31
152	07.08.2019 07:00 – 07.08.2019 08:00 (CET)	37	66.13
153	07.08.2019 08:00 – 07.08.2019 09:00 (CET)	34	69.54
154	07.08.2019 09:00 – 07.08.2019 10:00 (CET)	31	72.18
155	07.08.2019 10:00 – 07.08.2019 11:00 (CET)	31	73.2
156	07.08.2019 11:00 – 07.08.2019 12:00 (CET)	33	73.66
157	07.08.2019 12:00 – 07.08.2019 13:00 (CET)	38	72.09
158	07.08.2019 13:00 – 07.08.2019 14:00 (CET)	49	68.01
159	07.08.2019 14:00 – 07.08.2019 15:00 (CET)	52	63.65
160	07.08.2019 15:00 – 07.08.2019 16:00 (CET)	43	68.96
161	07.08.2019 16:00 – 07.08.2019 17:00 (CET)	37	66.2
162	07.08.2019 17:00 – 07.08.2019 18:00 (CET)	31	67.34
163	07.08.2019 18:00 – 07.08.2019 19:00 (CET)	23	68.81
164	07.08.2019 19:00 – 07.08.2019 20:00 (CET)	18	68.96
165	07.08.2019 20:00 – 07.08.2019 21:00 (CET)	12	68.97
166	07.08.2019 21:00 – 07.08.2019 22:00 (CET)	10	68.96

Appendix 1 continued

Number	Time	Wind MWh	Price, euro
167	07.08.2019 22:00 – 07.08.2019 23:00 (CET)	12	39.87
168	07.08.2019 23:00 – 08.08.2019 00:00 (CET)	11	38.89
169	08.08.2019 00:00 – 08.08.2019 01:00 (CET)	33	40.03
170	08.08.2019 01:00 – 08.08.2019 02:00 (CET)	43	35.38
171	08.08.2019 02:00 – 08.08.2019 03:00 (CET)	49	35.04
172	08.08.2019 03:00 – 08.08.2019 04:00 (CET)	43	34.95
173	08.08.2019 04:00 – 08.08.2019 05:00 (CET)	37	35.38
174	08.08.2019 05:00 – 08.08.2019 06:00 (CET)	31	57.81
175	08.08.2019 06:00 – 08.08.2019 07:00 (CET)	27	61.72
176	08.08.2019 07:00 – 08.08.2019 08:00 (CET)	29	66.28
177	08.08.2019 08:00 – 08.08.2019 09:00 (CET)	31	71.18
178	08.08.2019 09:00 – 08.08.2019 10:00 (CET)	32	69.14
179	08.08.2019 10:00 – 08.08.2019 11:00 (CET)	42	68.21
180	08.08.2019 11:00 – 08.08.2019 12:00 (CET)	65	68.28
181	08.08.2019 12:00 – 08.08.2019 13:00 (CET)	86	68.79
182	08.08.2019 13:00 – 08.08.2019 14:00 (CET)	109	68.3
183	08.08.2019 14:00 – 08.08.2019 15:00 (CET)	135	70.92
184	08.08.2019 15:00 – 08.08.2019 16:00 (CET)	168	70.14
185	08.08.2019 16:00 – 08.08.2019 17:00 (CET)	209	68.08
186	08.08.2019 17:00 – 08.08.2019 18:00 (CET)	223	67.12
187	08.08.2019 18:00 – 08.08.2019 19:00 (CET)	206	68.11
188	08.08.2019 19:00 – 08.08.2019 20:00 (CET)	180	68.05
189	08.08.2019 20:00 – 08.08.2019 21:00 (CET)	161	68.66
190	08.08.2019 21:00 – 08.08.2019 22:00 (CET)	157	49.96
191	08.08.2019 22:00 – 08.08.2019 23:00 (CET)	158	40.98
192	08.08.2019 23:00 – 09.08.2019 00:00 (CET)	160	39.04
193	09.08.2019 00:00 – 09.08.2019 01:00 (CET)	124	36.23
194	09.08.2019 01:00 – 09.08.2019 02:00 (CET)	125	35
195	09.08.2019 02:00 – 09.08.2019 03:00 (CET)	122	33.97
196	09.08.2019 03:00 – 09.08.2019 04:00 (CET)	118	34.06
197	09.08.2019 04:00 – 09.08.2019 05:00 (CET)	115	33.83
198	09.08.2019 05:00 – 09.08.2019 06:00 (CET)	103	37.7
199	09.08.2019 06:00 – 09.08.2019 07:00 (CET)	91	61.54
200	09.08.2019 07:00 – 09.08.2019 08:00 (CET)	84	66.26
201	09.08.2019 08:00 – 09.08.2019 09:00 (CET)	85	68.05
202	09.08.2019 09:00 – 09.08.2019 10:00 (CET)	88	68.21
203	09.08.2019 10:00 – 09.08.2019 11:00 (CET)	86	68.05
204	09.08.2019 11:00 – 09.08.2019 12:00 (CET)	88	67.99
205	09.08.2019 12:00 – 09.08.2019 13:00 (CET)	91	68.27
206	09.08.2019 13:00 – 09.08.2019 14:00 (CET)	93	67.21
207	09.08.2019 14:00 – 09.08.2019 15:00 (CET)	93	67.27
208	09.08.2019 15:00 – 09.08.2019 16:00 (CET)	96	68.26

Appendix 1 continued

Number	Time	Wind MWh	Price, euro
209	09.08.2019 16:00 – 09.08.2019 17:00 (CET)	101	68.23
210	09.08.2019 17:00 – 09.08.2019 18:00 (CET)	96	68.01
211	09.08.2019 18:00 – 09.08.2019 19:00 (CET)	85	67.3
212	09.08.2019 19:00 – 09.08.2019 20:00 (CET)	70	67.98
213	09.08.2019 20:00 – 09.08.2019 21:00 (CET)	64	42.79
214	09.08.2019 21:00 – 09.08.2019 22:00 (CET)	62	42.75
215	09.08.2019 22:00 – 09.08.2019 23:00 (CET)	58	35.33
216	09.08.2019 23:00 – 10.08.2019 00:00 (CET)	46	37.81
217	10.08.2019 00:00 – 10.08.2019 01:00 (CET)	31	34.87
218	10.08.2019 01:00 – 10.08.2019 02:00 (CET)	20	34.67
219	10.08.2019 02:00 – 10.08.2019 03:00 (CET)	13	33.92
220	10.08.2019 03:00 – 10.08.2019 04:00 (CET)	8	32.73
221	10.08.2019 04:00 – 10.08.2019 05:00 (CET)	5	31.7
222	10.08.2019 05:00 – 10.08.2019 06:00 (CET)	3	31.42
223	10.08.2019 06:00 – 10.08.2019 07:00 (CET)	4	32.17
224	10.08.2019 07:00 – 10.08.2019 08:00 (CET)	7	33.99
225	10.08.2019 08:00 – 10.08.2019 09:00 (CET)	10	35.24
226	10.08.2019 09:00 – 10.08.2019 10:00 (CET)	16	40.72
227	10.08.2019 10:00 – 10.08.2019 11:00 (CET)	24	40.52
228	10.08.2019 11:00 – 10.08.2019 12:00 (CET)	37	40.2
229	10.08.2019 12:00 – 10.08.2019 13:00 (CET)	58	40.89
230	10.08.2019 13:00 – 10.08.2019 14:00 (CET)	71	40.11
231	10.08.2019 14:00 – 10.08.2019 15:00 (CET)	84	40.12
232	10.08.2019 15:00 – 10.08.2019 16:00 (CET)	98	40.11
233	10.08.2019 16:00 – 10.08.2019 17:00 (CET)	113	39.67
234	10.08.2019 17:00 – 10.08.2019 18:00 (CET)	128	40.2
235	10.08.2019 18:00 – 10.08.2019 19:00 (CET)	155	42.69
236	10.08.2019 19:00 – 10.08.2019 20:00 (CET)	180	40.02
237	10.08.2019 20:00 – 10.08.2019 21:00 (CET)	188	34
238	10.08.2019 21:00 – 10.08.2019 22:00 (CET)	181	32.43
239	10.08.2019 22:00 – 10.08.2019 23:00 (CET)	171	31.83
240	10.08.2019 23:00 – 11.08.2019 00:00 (CET)	152	32.01
241	11.08.2019 00:00 – 11.08.2019 01:00 (CET)	76	28.84
242	11.08.2019 01:00 – 11.08.2019 02:00 (CET)	64	21.14
243	11.08.2019 02:00 – 11.08.2019 03:00 (CET)	62	14.55
244	11.08.2019 03:00 – 11.08.2019 04:00 (CET)	71	12.7
245	11.08.2019 04:00 – 11.08.2019 05:00 (CET)	77	13.13
246	11.08.2019 05:00 – 11.08.2019 06:00 (CET)	79	13.62
247	11.08.2019 06:00 – 11.08.2019 07:00 (CET)	73	14.91
248	11.08.2019 07:00 – 11.08.2019 08:00 (CET)	67	21.19
249	11.08.2019 08:00 – 11.08.2019 09:00 (CET)	72	29.11
250	11.08.2019 09:00 – 11.08.2019 10:00 (CET)	87	31.99

Number	**Time**	**Wind MWh**	**Price, euro**
251	11.08.2019 10:00 – 11.08.2019 11:00 (CET)	107	33.21
252	11.08.2019 11:00 – 11.08.2019 12:00 (CET)	131	33.25
253	11.08.2019 12:00 – 11.08.2019 13:00 (CET)	159	32.13
254	11.08.2019 13:00 – 11.08.2019 14:00 (CET)	185	31.96
255	11.08.2019 14:00 – 11.08.2019 15:00 (CET)	193	31.62
256	11.08.2019 15:00 – 11.08.2019 16:00 (CET)	176	32.47
257	11.08.2019 16:00 – 11.08.2019 17:00 (CET)	155	32.61
258	11.08.2019 17:00 – 11.08.2019 18:00 (CET)	126	34.01
259	11.08.2019 18:00 – 11.08.2019 19:00 (CET)	90	35.97
260	11.08.2019 19:00 – 11.08.2019 20:00 (CET)	63	37.1
261	11.08.2019 20:00 – 11.08.2019 21:00 (CET)	49	37.68
262	11.08.2019 21:00 – 11.08.2019 22:00 (CET)	46	37.75
263	11.08.2019 22:00 – 11.08.2019 23:00 (CET)	46	37.59
264	11.08.2019 23:00 – 12.08.2019 00:00 (CET)	47	36.4
265	12.08.2019 00:00 – 12.08.2019 01:00 (CET)	59	34.32
266	12.08.2019 01:00 – 12.08.2019 02:00 (CET)	72	30.04
267	12.08.2019 02:00 – 12.08.2019 03:00 (CET)	85	28.38
268	12.08.2019 03:00 – 12.08.2019 04:00 (CET)	95	27.5
269	12.08.2019 04:00 – 12.08.2019 05:00 (CET)	107	28.1
270	12.08.2019 05:00 – 12.08.2019 06:00 (CET)	110	32.32
271	12.08.2019 06:00 – 12.08.2019 07:00 (CET)	101	60.93
272	12.08.2019 07:00 – 12.08.2019 08:00 (CET)	91	65
273	12.08.2019 08:00 – 12.08.2019 09:00 (CET)	79	68.25
274	12.08.2019 09:00 – 12.08.2019 10:00 (CET)	69	68.25
275	12.08.2019 10:00 – 12.08.2019 11:00 (CET)	67	68.28
276	12.08.2019 11:00 – 12.08.2019 12:00 (CET)	66	66.35
277	12.08.2019 12:00 – 12.08.2019 13:00 (CET)	59	67.09
278	12.08.2019 13:00 – 12.08.2019 14:00 (CET)	50	64.64
279	12.08.2019 14:00 – 12.08.2019 15:00 (CET)	45	62.53
280	12.08.2019 15:00 – 12.08.2019 16:00 (CET)	44	62.76
281	12.08.2019 16:00 – 12.08.2019 17:00 (CET)	43	64.66
282	12.08.2019 17:00 – 12.08.2019 18:00 (CET)	42	61.11
283	12.08.2019 18:00 – 12.08.2019 19:00 (CET)	42	60.98
284	12.08.2019 19:00 – 12.08.2019 20:00 (CET)	42	65.02
285	12.08.2019 20:00 – 12.08.2019 21:00 (CET)	43	38.82
286	12.08.2019 21:00 – 12.08.2019 22:00 (CET)	48	38.82
287	12.08.2019 22:00 – 12.08.2019 23:00 (CET)	52	38.33
288	12.08.2019 23:00 – 13.08.2019 00:00 (CET)	53	36.13
289	13.08.2019 00:00 – 13.08.2019 01:00 (CET)	33	34.97
290	13.08.2019 01:00 – 13.08.2019 02:00 (CET)	31	34.01
291	13.08.2019 02:00 – 13.08.2019 03:00 (CET)	27	33.07
292	13.08.2019 03:00 – 13.08.2019 04:00 (CET)	23	33.27

Number	Time	Wind MWh	Price, euro
293	13.08.2019 04:00 – 13.08.2019 05:00 (CET)	22	33.19
294	13.08.2019 05:00 – 13.08.2019 06:00 (CET)	21	35.31
295	13.08.2019 06:00 – 13.08.2019 07:00 (CET)	22	61.98
296	13.08.2019 07:00 – 13.08.2019 08:00 (CET)	24	67.07
297	13.08.2019 08:00 – 13.08.2019 09:00 (CET)	27	71.31
298	13.08.2019 09:00 – 13.08.2019 10:00 (CET)	35	72.03
299	13.08.2019 10:00 – 13.08.2019 11:00 (CET)	42	72.29
300	13.08.2019 11:00 – 13.08.2019 12:00 (CET)	49	72.44
301	13.08.2019 12:00 – 13.08.2019 13:00 (CET)	62	72.78
302	13.08.2019 13:00 – 13.08.2019 14:00 (CET)	68	72.71
303	13.08.2019 14:00 – 13.08.2019 15:00 (CET)	70	69.29
304	13.08.2019 15:00 – 13.08.2019 16:00 (CET)	63	69.73
305	13.08.2019 16:00 – 13.08.2019 17:00 (CET)	60	68.23
306	13.08.2019 17:00 – 13.08.2019 18:00 (CET)	55	67.93
307	13.08.2019 18:00 – 13.08.2019 19:00 (CET)	49	66.9
308	13.08.2019 19:00 – 13.08.2019 20:00 (CET)	43	67.87
309	13.08.2019 20:00 – 13.08.2019 21:00 (CET)	51	51.33
310	13.08.2019 21:00 – 13.08.2019 22:00 (CET)	68	46.77
311	13.08.2019 22:00 – 13.08.2019 23:00 (CET)	83	37.16
312	13.08.2019 23:00 – 14.08.2019 00:00 (CET)	90	35.43
313	14.08.2019 00:00 – 14.08.2019 01:00 (CET)	80	32.72
314	14.08.2019 01:00 – 14.08.2019 02:00 (CET)	86	30.45
315	14.08.2019 02:00 – 14.08.2019 03:00 (CET)	93	28.43
316	14.08.2019 03:00 – 14.08.2019 04:00 (CET)	93	28.27
317	14.08.2019 04:00 – 14.08.2019 05:00 (CET)	89	29.68
318	14.08.2019 05:00 – 14.08.2019 06:00 (CET)	83	34.98
319	14.08.2019 06:00 – 14.08.2019 07:00 (CET)	69	61.27
320	14.08.2019 07:00 – 14.08.2019 08:00 (CET)	59	71.37
321	14.08.2019 08:00 – 14.08.2019 09:00 (CET)	55	71.86
322	14.08.2019 09:00 – 14.08.2019 10:00 (CET)	57	70.14
323	14.08.2019 10:00 – 14.08.2019 11:00 (CET)	64	69.44
324	14.08.2019 11:00 – 14.08.2019 12:00 (CET)	67	69.91
325	14.08.2019 12:00 – 14.08.2019 13:00 (CET)	73	69.96
326	14.08.2019 13:00 – 14.08.2019 14:00 (CET)	76	68.75
327	14.08.2019 14:00 – 14.08.2019 15:00 (CET)	76	68.4
328	14.08.2019 15:00 – 14.08.2019 16:00 (CET)	77	66.35
329	14.08.2019 16:00 – 14.08.2019 17:00 (CET)	77	67.38
330	14.08.2019 17:00 – 14.08.2019 18:00 (CET)	75	67.81
331	14.08.2019 18:00 – 14.08.2019 19:00 (CET)	68	69.78
332	14.08.2019 19:00 – 14.08.2019 20:00 (CET)	61	71.31
333	14.08.2019 20:00 – 14.08.2019 21:00 (CET)	60	66.3
334	14.08.2019 21:00 – 14.08.2019 22:00 (CET)	67	51.48

Appendix 1 continued

Number	Time	Wind MWh	Price, euro
335	14.08.2019 22:00 – 14.08.2019 23:00 (CET)	79	36.91
336	14.08.2019 23:00 – 15.08.2019 00:00 (CET)	80	35.09
337	15.08.2019 00:00 – 15.08.2019 01:00 (CET)	88	33.01
338	15.08.2019 01:00 – 15.08.2019 02:00 (CET)	89	31.45
339	15.08.2019 02:00 – 15.08.2019 03:00 (CET)	85	29.34
340	15.08.2019 03:00 – 15.08.2019 04:00 (CET)	80	27.81
341	15.08.2019 04:00 – 15.08.2019 05:00 (CET)	81	26.7
342	15.08.2019 05:00 – 15.08.2019 06:00 (CET)	74	30.58
343	15.08.2019 06:00 – 15.08.2019 07:00 (CET)	62	52.84
344	15.08.2019 07:00 – 15.08.2019 08:00 (CET)	47	55.11
345	15.08.2019 08:00 – 15.08.2019 09:00 (CET)	42	56.86
346	15.08.2019 09:00 – 15.08.2019 10:00 (CET)	53	57.62
347	15.08.2019 10:00 – 15.08.2019 11:00 (CET)	62	58.63
348	15.08.2019 11:00 – 15.08.2019 12:00 (CET)	67	58.75
349	15.08.2019 12:00 – 15.08.2019 13:00 (CET)	66	58.8
350	15.08.2019 13:00 – 15.08.2019 14:00 (CET)	65	58.76
351	15.08.2019 14:00 – 15.08.2019 15:00 (CET)	61	57.97
352	15.08.2019 15:00 – 15.08.2019 16:00 (CET)	55	58.67
353	15.08.2019 16:00 – 15.08.2019 17:00 (CET)	42	56.96
354	15.08.2019 17:00 – 15.08.2019 18:00 (CET)	34	57.49
355	15.08.2019 18:00 – 15.08.2019 19:00 (CET)	23	58.89
356	15.08.2019 19:00 – 15.08.2019 20:00 (CET)	13	64.93
357	15.08.2019 20:00 – 15.08.2019 21:00 (CET)	10	39.93
358	15.08.2019 21:00 – 15.08.2019 22:00 (CET)	12	36.15
359	15.08.2019 22:00 – 15.08.2019 23:00 (CET)	21	35.07
360	15.08.2019 23:00 – 16.08.2019 00:00 (CET)	32	33.33
361	16.08.2019 00:00 – 16.08.2019 01:00 (CET)	57	31.11
362	16.08.2019 01:00 – 16.08.2019 02:00 (CET)	80	29.53
363	16.08.2019 02:00 – 16.08.2019 03:00 (CET)	92	28.79
364	16.08.2019 03:00 – 16.08.2019 04:00 (CET)	101	29.01
365	16.08.2019 04:00 – 16.08.2019 05:00 (CET)	103	29.93
366	16.08.2019 05:00 – 16.08.2019 06:00 (CET)	102	31.99
367	16.08.2019 06:00 – 16.08.2019 07:00 (CET)	91	54.9
368	16.08.2019 07:00 – 16.08.2019 08:00 (CET)	75	61.11
369	16.08.2019 08:00 – 16.08.2019 09:00 (CET)	57	65.33
370	16.08.2019 09:00 – 16.08.2019 10:00 (CET)	53	66.07
371	16.08.2019 10:00 – 16.08.2019 11:00 (CET)	59	66.52
372	16.08.2019 11:00 – 16.08.2019 12:00 (CET)	63	66.33
373	16.08.2019 12:00 – 16.08.2019 13:00 (CET)	60	66.27
374	16.08.2019 13:00 – 16.08.2019 14:00 (CET)	57	66.23
375	16.08.2019 14:00 – 16.08.2019 15:00 (CET)	45	64.59
376	16.08.2019 15:00 – 16.08.2019 16:00 (CET)	35	65.02

Appendix 1 continued

Number	Time	Wind MWh	Price, euro
377	16.08.2019 16:00 – 16.08.2019 17:00 (CET)	28	64.91
378	16.08.2019 17:00 – 16.08.2019 18:00 (CET)	23	62.85
379	16.08.2019 18:00 – 16.08.2019 19:00 (CET)	24	62.11
380	16.08.2019 19:00 – 16.08.2019 20:00 (CET)	30	59.53
381	16.08.2019 20:00 – 16.08.2019 21:00 (CET)	38	39.61
382	16.08.2019 21:00 – 16.08.2019 22:00 (CET)	52	37.13
383	16.08.2019 22:00 – 16.08.2019 23:00 (CET)	65	35.99
384	16.08.2019 23:00 – 17.08.2019 00:00 (CET)	74	31.96
385	17.08.2019 00:00 – 17.08.2019 01:00 (CET)	34	32.22
386	17.08.2019 01:00 – 17.08.2019 02:00 (CET)	31	27.39
387	17.08.2019 02:00 – 17.08.2019 03:00 (CET)	29	23.54
388	17.08.2019 03:00 – 17.08.2019 04:00 (CET)	26	18.62
389	17.08.2019 04:00 – 17.08.2019 05:00 (CET)	22	13.91
390	17.08.2019 05:00 – 17.08.2019 06:00 (CET)	17	15.08
391	17.08.2019 06:00 – 17.08.2019 07:00 (CET)	12	25.53
392	17.08.2019 07:00 – 17.08.2019 08:00 (CET)	9	30.55
393	17.08.2019 08:00 – 17.08.2019 09:00 (CET)	9	58.65
394	17.08.2019 09:00 – 17.08.2019 10:00 (CET)	13	59.83
395	17.08.2019 10:00 – 17.08.2019 11:00 (CET)	21	59.88
396	17.08.2019 11:00 – 17.08.2019 12:00 (CET)	40	41.8
397	17.08.2019 12:00 – 17.08.2019 13:00 (CET)	53	65.35
398	17.08.2019 13:00 – 17.08.2019 14:00 (CET)	66	63.97
399	17.08.2019 14:00 – 17.08.2019 15:00 (CET)	64	59.34
400	17.08.2019 15:00 – 17.08.2019 16:00 (CET)	47	30.94
401	17.08.2019 16:00 – 17.08.2019 17:00 (CET)	38	41.55
402	17.08.2019 17:00 – 17.08.2019 18:00 (CET)	31	32.72
403	17.08.2019 18:00 – 17.08.2019 19:00 (CET)	22	42
404	17.08.2019 19:00 – 17.08.2019 20:00 (CET)	19	58.67
405	17.08.2019 20:00 – 17.08.2019 21:00 (CET)	21	59.23
406	17.08.2019 21:00 – 17.08.2019 22:00 (CET)	32	35.27
407	17.08.2019 22:00 – 17.08.2019 23:00 (CET)	55	34.56
408	17.08.2019 23:00 – 18.08.2019 00:00 (CET)	68	33.29
409	18.08.2019 00:00 – 18.08.2019 01:00 (CET)	51	31.8
410	18.08.2019 01:00 – 18.08.2019 02:00 (CET)	60	28.61
411	18.08.2019 02:00 – 18.08.2019 03:00 (CET)	63	28.73
412	18.08.2019 03:00 – 18.08.2019 04:00 (CET)	66	29
413	18.08.2019 04:00 – 18.08.2019 05:00 (CET)	68	28.94
414	18.08.2019 05:00 – 18.08.2019 06:00 (CET)	64	28.48
415	18.08.2019 06:00 – 18.08.2019 07:00 (CET)	58	31.08
416	18.08.2019 07:00 – 18.08.2019 08:00 (CET)	43	33.26
417	18.08.2019 08:00 – 18.08.2019 09:00 (CET)	36	33.62
418	18.08.2019 09:00 – 18.08.2019 10:00 (CET)	37	34.27

Appendix 1 continued

Number	**Time**	**Wind MWh**	**Price, euro**
419	18.08.2019 10:00 – 18.08.2019 11:00 (CET)	54	42.48
420	18.08.2019 11:00 – 18.08.2019 12:00 (CET)	68	53.23
421	18.08.2019 12:00 – 18.08.2019 13:00 (CET)	82	51.39
422	18.08.2019 13:00 – 18.08.2019 14:00 (CET)	90	50.27
423	18.08.2019 14:00 – 18.08.2019 15:00 (CET)	93	50.25
424	18.08.2019 15:00 – 18.08.2019 16:00 (CET)	88	34.69
425	18.08.2019 16:00 – 18.08.2019 17:00 (CET)	82	35.07
426	18.08.2019 17:00 – 18.08.2019 18:00 (CET)	79	35.54
427	18.08.2019 18:00 – 18.08.2019 19:00 (CET)	90	35.27
428	18.08.2019 19:00 – 18.08.2019 20:00 (CET)	110	49.52
429	18.08.2019 20:00 – 18.08.2019 21:00 (CET)	136	43.28
430	18.08.2019 21:00 – 18.08.2019 22:00 (CET)	159	36.78
431	18.08.2019 22:00 – 18.08.2019 23:00 (CET)	177	35.83
432	18.08.2019 23:00 – 19.08.2019 00:00 (CET)	184	33.81
433	19.08.2019 00:00 – 19.08.2019 01:00 (CET)	195	29.59
434	19.08.2019 01:00 – 19.08.2019 02:00 (CET)	182	27.45
435	19.08.2019 02:00 – 19.08.2019 03:00 (CET)	165	26.86
436	19.08.2019 03:00 – 19.08.2019 04:00 (CET)	151	28.16
437	19.08.2019 04:00 – 19.08.2019 05:00 (CET)	137	27.06
438	19.08.2019 05:00 – 19.08.2019 06:00 (CET)	115	31.96
439	19.08.2019 06:00 – 19.08.2019 07:00 (CET)	98	53.45
440	19.08.2019 07:00 – 19.08.2019 08:00 (CET)	88	59.97
441	19.08.2019 08:00 – 19.08.2019 09:00 (CET)	88	60.41
442	19.08.2019 09:00 – 19.08.2019 10:00 (CET)	97	54.84
443	19.08.2019 10:00 – 19.08.2019 11:00 (CET)	105	55.42
444	19.08.2019 11:00 – 19.08.2019 12:00 (CET)	109	59.16
445	19.08.2019 12:00 – 19.08.2019 13:00 (CET)	105	61.8
446	19.08.2019 13:00 – 19.08.2019 14:00 (CET)	101	61.48
447	19.08.2019 14:00 – 19.08.2019 15:00 (CET)	87	56.01
448	19.08.2019 15:00 – 19.08.2019 16:00 (CET)	75	54.65
449	19.08.2019 16:00 – 19.08.2019 17:00 (CET)	62	55.03
450	19.08.2019 17:00 – 19.08.2019 18:00 (CET)	48	55.26
451	19.08.2019 18:00 – 19.08.2019 19:00 (CET)	38	58.09
452	19.08.2019 19:00 – 19.08.2019 20:00 (CET)	26	57.98
453	19.08.2019 20:00 – 19.08.2019 21:00 (CET)	19	47.67
454	19.08.2019 21:00 – 19.08.2019 22:00 (CET)	18	36.53
455	19.08.2019 22:00 – 19.08.2019 23:00 (CET)	17	35.84
456	19.08.2019 23:00 – 20.08.2019 00:00 (CET)	18	34.08
457	20.08.2019 00:00 – 20.08.2019 01:00 (CET)	20	31.38
458	20.08.2019 01:00 – 20.08.2019 02:00 (CET)	21	29.74
459	20.08.2019 02:00 – 20.08.2019 03:00 (CET)	24	29.58
460	20.08.2019 03:00 – 20.08.2019 04:00 (CET)	26	28.67

Number	Time	Wind MWh	Price, euro
461	20.08.2019 04:00 – 20.08.2019 05:00 (CET)	29	30.08
462	20.08.2019 05:00 – 20.08.2019 06:00 (CET)	29	33.33
463	20.08.2019 06:00 – 20.08.2019 07:00 (CET)	24	51.49
464	20.08.2019 07:00 – 20.08.2019 08:00 (CET)	20	55.02
465	20.08.2019 08:00 – 20.08.2019 09:00 (CET)	18	58.33
466	20.08.2019 09:00 – 20.08.2019 10:00 (CET)	23	55.38
467	20.08.2019 10:00 – 20.08.2019 11:00 (CET)	33	54.52
468	20.08.2019 11:00 – 20.08.2019 12:00 (CET)	38	54.02
469	20.08.2019 12:00 – 20.08.2019 13:00 (CET)	49	55.51
470	20.08.2019 13:00 – 20.08.2019 14:00 (CET)	55	54.93
471	20.08.2019 14:00 – 20.08.2019 15:00 (CET)	57	53.09
472	20.08.2019 15:00 – 20.08.2019 16:00 (CET)	52	53.01
473	20.08.2019 16:00 – 20.08.2019 17:00 (CET)	49	53.07
474	20.08.2019 17:00 – 20.08.2019 18:00 (CET)	38	53.15
475	20.08.2019 18:00 – 20.08.2019 19:00 (CET)	31	54.98
476	20.08.2019 19:00 – 20.08.2019 20:00 (CET)	25	57.07
477	20.08.2019 20:00 – 20.08.2019 21:00 (CET)	21	39.29
478	20.08.2019 21:00 – 20.08.2019 22:00 (CET)	17	36.98
479	20.08.2019 22:00 – 20.08.2019 23:00 (CET)	16	35.96
480	20.08.2019 23:00 – 21.08.2019 00:00 (CET)	17	34.99
481	21.08.2019 00:00 – 21.08.2019 01:00 (CET)	8	33.07
482	21.08.2019 01:00 – 21.08.2019 02:00 (CET)	9	33.11
483	21.08.2019 02:00 – 21.08.2019 03:00 (CET)	12	32.01
484	21.08.2019 03:00 – 21.08.2019 04:00 (CET)	13	31.23
485	21.08.2019 04:00 – 21.08.2019 05:00 (CET)	17	31.93
486	21.08.2019 05:00 – 21.08.2019 06:00 (CET)	24	33.97
487	21.08.2019 06:00 – 21.08.2019 07:00 (CET)	32	60.45
488	21.08.2019 07:00 – 21.08.2019 08:00 (CET)	47	66.2
489	21.08.2019 08:00 – 21.08.2019 09:00 (CET)	55	68.65
490	21.08.2019 09:00 – 21.08.2019 10:00 (CET)	55	68.25
491	21.08.2019 10:00 – 21.08.2019 11:00 (CET)	50	67.7
492	21.08.2019 11:00 – 21.08.2019 12:00 (CET)	48	68.72
493	21.08.2019 12:00 – 21.08.2019 13:00 (CET)	51	70.99
494	21.08.2019 13:00 – 21.08.2019 14:00 (CET)	56	68.3
495	21.08.2019 14:00 – 21.08.2019 15:00 (CET)	77	68.07
496	21.08.2019 15:00 – 21.08.2019 16:00 (CET)	83	68.39

Appendix 2

Survey Questionnaire on Latvian electricity consumers' awareness and its related factors

Questionnaire includes questions and answers options used in the Thesis research on Latvian electricity consumers' awareness and its related factors.

Anketas jautājumi un atbilžu varianti, kas izmantoti promocijas darba pētījumā par Latvijas elektroenerģijas patērētāju informētību un ar to saistītiem faktoriem.

Please, help us to learn your daily routine to provide you with better technology in your coming future.

Prosumers: Prosumers are the pro-active consumers who play a vital role in generating benefits both for themselves and for society and the country.

Please select the one best option that best describes you.

1. Your gender?

a. Male

b. Female

c. I don’t want to share

2. Your age group?

a. 17 to 26

b. 27 to 36

c. 37 to 46

d. 47 to 56

e. 57 and above

3. To what extent you consider yourself a prosumer?

1	**2**	**3**	**4**	**5**

4. How often do you need extra electricity?

a. Very often

b. Often

c. Sometimes

d. Seldom

5. Which kind of energy would you prefer as a prosumer?

a. residential (produce electricity on own property by installing solar PV panels

b. community / cooperative energy – housing associations, foundations and charities

c. commercial prosumers – at department stores, office buildings, industry and other business entities by self-consume (cost savings)

d. public – schools, hospitals and other public institutions that self-generate electricity

6. What heating types do you have in your home?

a. Gas-fired boiler and central heating

b. Storage heaters

c. Warm air system

d. Wood burning stove and solar thermal

7. To what extent you agree to make your home more energy efficient?

Strongly disagree	**Disagree**	**Neutral**	**Agree**	**Strongly agree**

8. To what extent you are satisfied with your electricity provider?

Very unsatisfied	**Unsatisfied**	**Neutral**	**Satisfied**	**Very satisfied**

9. To what extent you agree that self-generated electricity is the better option?

Strongly disagree	**Disagree**	**Neutral**	**Agree**	**Strongly agree**

10. How many kilowatt-hours of electricity do you use monthly?

a. Below 150

b. 150 to 200

c. 200 to 250

d. 250 to 300

e. More than 300

11. How often do you/ your household use an air conditioner in summer?

Very often	**Often**	**Sometimes**	**Rarely**	**Very rarely**

12. What time of the day do you usually use your air conditioner?

a. Morning

b. Afternoon

c. Evening

d. Night

e. All-day

13. How often do you / your household use a heater in winter?

Very often	**Often**	**Sometimes**	**Rarely**	**Very rarely**

14. At what time of the day do you usually use your heater?

a. Morning
b. Afternoon
c. Evening
d. Night
e. All-day

15. Are any of your appliances programmed to work on a timer? If so, please select which ones?

a. I don't have any appliances set on a timer.
b. Dishwasher
c. Washing machine
d. Heater
e. Air conditioner
f. Television
g. Other: please specify

16. Are you familiar with solar panel technology?

a. Yes
b. No

17. Do you know how solar panel technology works?

a. Yes
b. No

Thank you very much for your precious time.